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NASA Lyndon B. Johnson Space Center
Houston, TX
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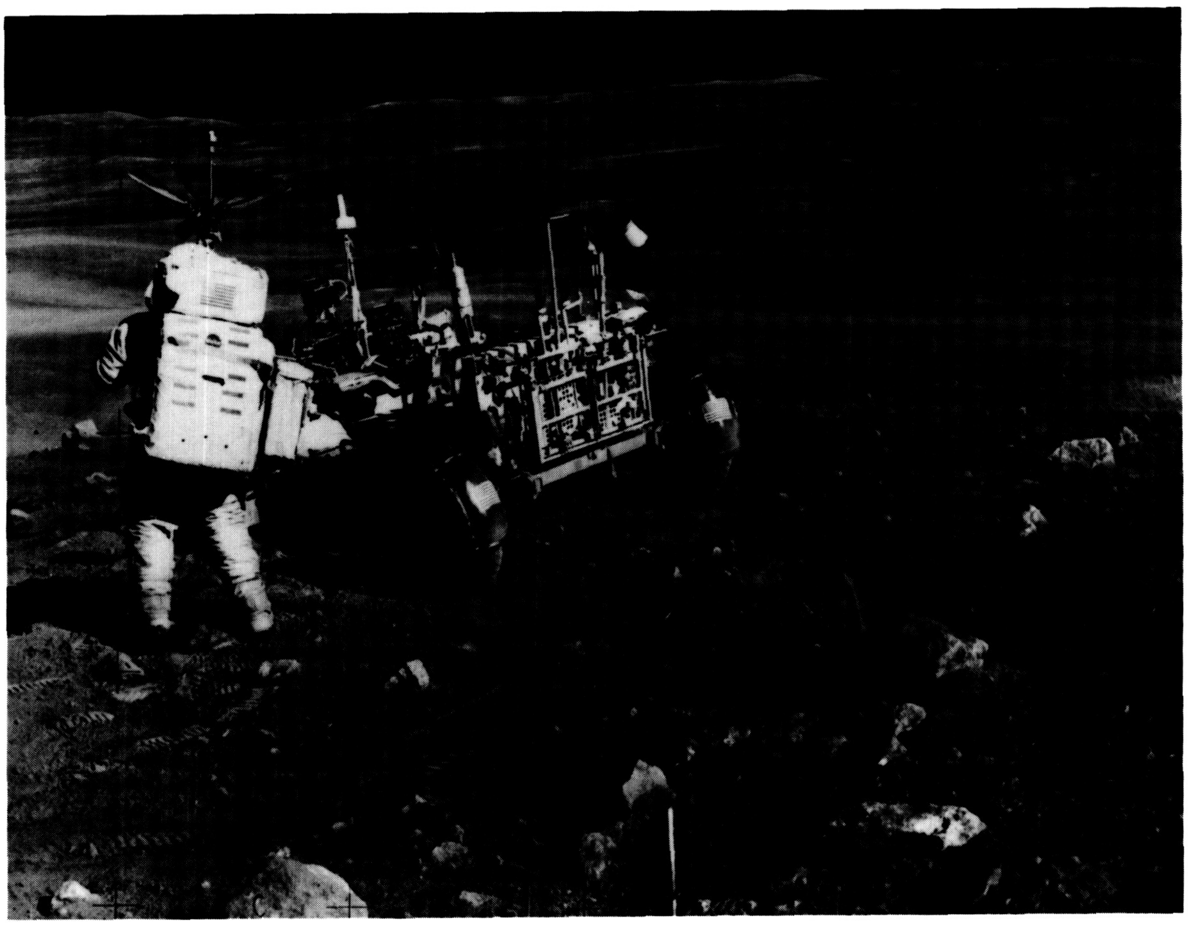
Advanced Extravehicular Activity Systems Requirements Definition Study



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1.0 SUMMARY

Since the first Extravehicular Activity (EVA) in the Gemini program, EVA has become increasingly important in space operations. Early EVA was used only for proof-of-concept studies (e.g. using a hand-held maneuvering unit for crew maneuvering tests) and secondary objectives (e.g. attaching tethers and retrieving packages). However, during the Apollo lunar surface activities, EVA became a fundamental part of space operations. While the use of EVA equipment allowed the crew to perform many crucial functions, the equipment was designed for short-duration missions only. Data gathered describing the lunar environment indicated that a system designed to support long-duration missions might be significantly different from Apollo technology or the 0-g state-of-the-art technology being developed for the Space Station. To date, little effort has been expended to identify, to define, or to determine unique advanced manned lunar EVA mission requirements, EVA hardware technology drivers, and environmental factors which can influence future manned space missions on the lunar surface. This study was focused directly on advanced EVA (AEVA) requirements, to provide a supporting data base for more widely scoped studies of future lunar operations involving EVA. Its purposes are to develop an understanding of the EVA technology requirements and to map a pathway from existing or developing technologies to an AEVA system capable of supporting long-duration missions on the lunar surface. It examined in detail the requirements of an AEVA system which must sustain the crewmembers life and permit productive work for long durations in the harsh lunar environment. While this environment places severe constraints on the crew and hardware, it also has features which can be used advantageously by hardware designers (e.g. improved load manipulation capabilities in 1/6 g). The three major tasks of this study were to:

- Conduct an EVA Mission and Environmental Survey/Definition,
- Develop EVA Hardware Design Requirements and Criteria, and
- Determine EVA Hardware Interface Accommodations Requirements.

A design reference mission (DRM) was formulated and used as a tool to develop and analyze the EVA system technology requirements. Study of the mission (which was selected to represent a high-risk, critical phase in development of a long-term manned lunar capability) highlighted many operational and infrastructure design issues that have a significant influence on the EVA system design.

Once the DRM was established, a description of the aspects of the lunar environment and geotechnical features that affect the EVA system was developed. This assessment included nominal conditions that would be encountered during the DRM and emergency or worst-case scenarios.

Then the EVA technology requirements and criteria were developed based on the DRM and the lunar environment. For each requirements area, the rationale and supporting data were compiled. The current EVA hardware (STS) and developmental (Space Station) EVA hardware were compared against these requirements to identify areas not met by hardware technologies. The technology areas that were identified where additional developments are required, include:

- Gloves,
- Suit design for walking comfort,
- Portable Life Support System (PLSS),
- Bearings and dust seals,
- Dust cleaning methodologies and tools,
- Design of habitat and suit/habitat interfaces to prevent dust infiltration,
- Suit materials to minimize dust pick-up and static charging, and

- Visors.

Associated technology areas with specific unique requirements for lunar operations are:

- Robotics/teleoperation,
- Communications, and
- Rescue/Medical emergency equipment.

For critical areas that had both long technology development lead times (>5 years) and significant unique, lunar-derived attributes, program descriptions, recommended funding levels, and schedules for development of EVA hardware to support long-duration missions were developed. The two most critical areas recommended for development are the:

- PLSS design to meet thermal requirements within acceptable weight and volume constraints, and
- Development of suit/equipment designs for lunar dust compatibility and cleanibility.

2.0 BACKGROUND

There is a resurgence of interest in a return to the Moon for pragmatic and scientific reasons, and as a logical step in extending the human presence into the Solar System. Lunar bases within the framework of space activities in the 21st century are receiving increased attention, and they have been proposed as part of the agenda for the national space program. The National Commission on Space concluded that "early outposts on the lunar surface are essential in the development of the space frontier. They will permit the extension of lunar exploration for the purposes of both scientific research and resource development (National Commission on Space, 1986, p. 138)." The Commission recommended "establishing the first lunar outpost within the next 20 years, and progressing to permanently occupied lunar bases within the following decade (National Commission on Space, 1986, p.140)."

A return to the moon presents an exciting challenge both scientifically and technologically. It offers the opportunity for humans to develop the capacity to live and work beyond the surface of the Earth, as well as to apply new technologies and systems in accordance with experience gained, available funding, and public support.

A potential driver for a return to the Moon is the mining of lunar resources, processing them, and manufacturing products such as lunar-derived oxygen for propellants and life support. Lunar-derived products could reduce transportation requirements from the Earth to the Moon and to other solar system destinations; provide shielding for manned habitats in high-Earth orbits; and supply construction materials for the space infrastructure which would enable major space projects such as telecommunications platforms and solar power satellites.

Although it will be possible to use automated equipment and robots to perform some of the activities on the Moon, human presence will be essential for the successful development of a lunar base and for performing the tasks associated with lunar resources utilization. Robots utilizing current technology can perform a variety of tasks, but only if they are well defined and extensively planned. Evolving technology will provide tools capable of performing some classes of unplanned activities, such as autonomous site investigation. For example, artificial intelligence (AI) is being developed to bridge the gap between the structured task environment and the variable environment in which humans operate. It will be a long time, however, before a dexterous robot (with near-human capability) can autonomously decide to go out on to the lunar surface, find a malfunctioning piece of equipment, and repair it. Teleoperation makes it possible for robots on the lunar surface to be controlled from the earth. However, time delays in transmitting data make teleoperation from earth difficult. In addition, unforeseen circumstances (such as those encountered in the past) will continue to be a crucial part of EVA thereby limiting the scope of activities that could be performed by teleoperated equipment. For example, a time delay in the teleoperation control loop from earth, or a completely pre-programmed sequence, would not have worked on the EVA's conducted on Shuttle flights 51-A and 51-D. Using teleoperation with the crew near the robot on the lunar surface will improve these problems. However, the crew's ability to perform EVA will be crucial to mission success for two reasons. First, robotic equipment (unless totally AI-controlled) will not be able to perceive rapidly as many aspects of the work environment as a human and could miss key data. Second, equipment and robots can and will malfunction. If survival-critical operations are being conducted when a robot failure occurs, there must be a rapidly deployable intelligent alternative which would be able to complete the task. Therefore, humans working on the lunar surface can and must engage in a wide variety of EVA tasks.

3.0 PURPOSE AND SCOPE

3.1 Purpose

This study focused on AEVA requirements, to provide a supporting data base for more widely scoped studies of future lunar missions involving EVA, and to develop a basis for planning future lunar EVAs. Specifically, the study was designed to understand the EVA technology requirements, and to map a pathway from existing or developing technologies to an AEVA system capable of supporting long-duration missions on the lunar surface.

3.2 Scope

This study examined in detail the requirements of an AEVA system which must sustain the crewmembers' life and which would permit productive work for long durations in the lunar environment. This environment places severe constraints on the crew and hardware, but it also has features which can be used advantageously by hardware designers (e.g. operation in 1/6 g). The major tasks of the study were to:

- Survey and define lunar EVA mission and environmental requirements,
- Develop EVA technology requirements and hardware design criteria to support EVA mission operations, and
- Identify EVA hardware interface accommodations requirements.

4.0 APPROACH

4.1 Overview

A DRM was formulated and used as a tool to develop and analyze the environmental description and the EVA system technology requirements. Study of the mission highlighted many operational and infrastructure design issues that have a significant influence on the EVA system design.

Using the DRM a description of the aspects of the lunar environment which would affect the EVA system was developed. This assessment included a description of nominal conditions that would be encountered during the DRM, as well as emergency or worst-case scenarios.

Then the EVA technology requirements and criteria were developed based on the DRM and the lunar environment. For each requirements area, requirements and supporting data were compiled. In addition, information regarding data limitations and requirements for additional investigation were also included. The current EVA hardware (STS) and developmental (Space Station) EVA hardware were then compared against these requirements to identify requirements not met by these known hardware technologies. For critical areas that have both long technology development lead times (>5 years) and significant unique lunar-specific attributes, program descriptions, recommended funding levels, and schedules for development of EVA hardware to support long-duration missions were developed.

The approach to collecting the data, developing the EVA hardware requirements, and the technology development plan was designed to take advantage of the knowledge of several crewmembers, NASA personnel, members of the Technical Advisory Group (TAG) and the Arthur D. Little study team members. The TAG consisted of EVA and lunar mission experts, providing practical experience and theoretical insights to AEVA issues and designs relevant to manned operations on the lunar surface.

In the following sections the design reference mission, environmental and geotechnical factors and physiological considerations are discussed as a prerequisite to the definition of EVA hardware and interface accommodation requirements, assessment of hardware capabilities, and plan for development of applicable technologies.

4.2 Acknowledgments

The study team wishes to acknowledge the active participation and guidance of Susan Schentrup, Technical Monitor, NASA, Lyndon B. Johnson Space Center (JSC). Discussions with Dr. George D. Nelson, Col. Sherwood C. Spring and Lt. Col. Jerry L. Ross, (current NASA crewmembers with Shuttle EVA experience) and Robert C. Trevino, (NASA, JSC, Crew Systems Training) all provided valuable information for the definition of the Design Reference Mission. Former crewmembers, Gerald Carr, Skylab, Dr. Harrison H. Schmitt, Apollo, and David Scott, Apollo, shared with us freely their EVA experience and their impressions of space suit performance. The contributions of Dr. Stuart Nachtwey, (NASA, JSC Life Sciences), to the data base on the space radiation environment is also gratefully acknowledged.

The study team greatly benefited from the discussions, constructive comments, and supplemental material supplied by the members of the TAG, including:

Wendel Mendell	NASA, JSC
Frederick Abeles	Grumman Space Systems Division
Michael Gan	Hamilton Standard
Robert Gray	ILC Dover
Victor Himel	Grumman Space Systems Division
John Sevier	Universities Space Research Association

Alan Thompson	Martin Marietta, Denver

The study team consisted of Dr. Peter E. Glaser, Dr. Beth Marcus, Carla Mond, Philip Churchill, Dr. John Collins, Katinka Csigi, and Arthur Post, of Arthur D. Little, Inc.

In addition, the Space Systems Division of the Grumman Corporation supported Arthur D. Little's efforts in this study.

5.0 DRM

5.1 Background

There are several phases of activity required to achieve the goal of human presence on the Moon, including: lunar base site selection, a temporary manned lunar base, and a permanently occupied base. There are expectations that if lunar resources become economically competitive with material transported from Earth, a self-supporting and, eventually, a self-sufficient human settlement could be created. A typical EVA mission on the lunar surface may encompass such activities as scientific research, development, or operational objectives. The EVA mission developed in this study is representative of those required to support the construction of a permanently occupied lunar base for a crew of four with tour of duty ranging from one to three months. Due to the extended stay-times, planning for and analyzing such a mission will require data beyond the existing lunar EVA mission data base which resulted from the Apollo program.

Post-Apollo lunar EVA missions will be concerned primarily with the construction of the lunar habitat from elements previously deployed on the lunar surface, shielding of the habitat, and preparing equipment and supplies that will be required for the development of lunar resources. Activities associated with these missions will require automated equipment (e.g., a bag-filling machine) and include surveys to select and obtain the most suitable lunar regolith for shielding purposes. More extensive sorties, including geo-physical research and site selection for future lunar resource mining, processing, and power plant siting may also be carried out. These missions will require the availability of lunar roving vehicles (LRV's) to accomplish more extensive traverses within a radius limited to about 20 minutes of travel so that a shielded shelter can be reached if a solar flare event warning is received.

The EVA mission considered in this study is the basis for establishing the requirements for all aspects of the protective atmosphere-containing suits, life support systems and related hardware. This EVA mission is sufficiently inclusive to ensure that the equipment, suits, and life support systems requirements, if met, will be adequate to support the phased development of a lunar base.

In order to develop a description of the technology required to support lunar EVA an understanding of the types of activities that will be performed and the environment in which the hardware will have to function is necessary. A DRM was developed to describe a detailed set of activities which would put demands on the hardware beyond known previous limits and which represent crucial functions required for long-duration lunar operations. This information was compiled from the literature and through discussions with NASA personnel.

5.2 Rationale

In reviewing the literature on the lunar surface missions, it was determined that the most demanding and hazardous environment for lunar EVA would be in the post-sortie, pre-lunar infrastructure time period. Existing Apollo/Shuttle-derived or developing Space Station technology can perform sortie-type operations. Conversely, once the lunar space infrastructure is in place, the EVA hardware will not need to have the autonomy required for early operations. Therefore, the most crucial application of EVA in the interim period will be the development of the lunar infrastructure elements. In addition to being the most critical, this interim period will have the highest level of risk, based on the well-documented requirements associated with using new hardware, in a new operational environment (e.g. Skylab).

The DRM that was developed is illustrated in Figures 1 through 9. The mission is not application specific. Its objective, instead, is to "initialize" the most crucial enabling element for long-duration manned missions: the manned lunar outpost. In accomplishing this mission, requirements will be placed on the EVA hardware which, if met, will assure that EVA technology will support the expansion of man's capability to live and to work on the Moon.

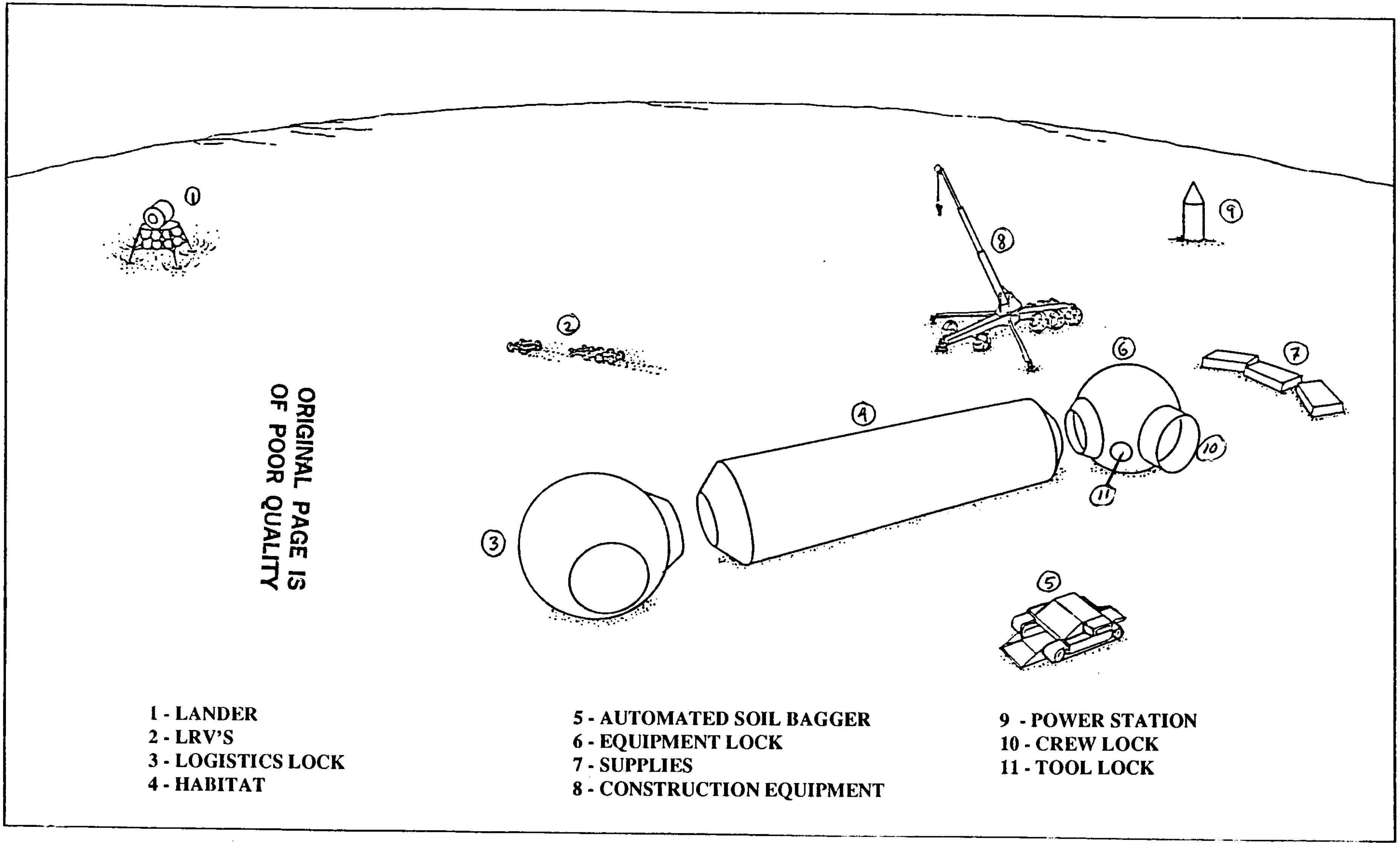

FIGURE 1: LANDER ARRIVES ON LUNAR SURFACE

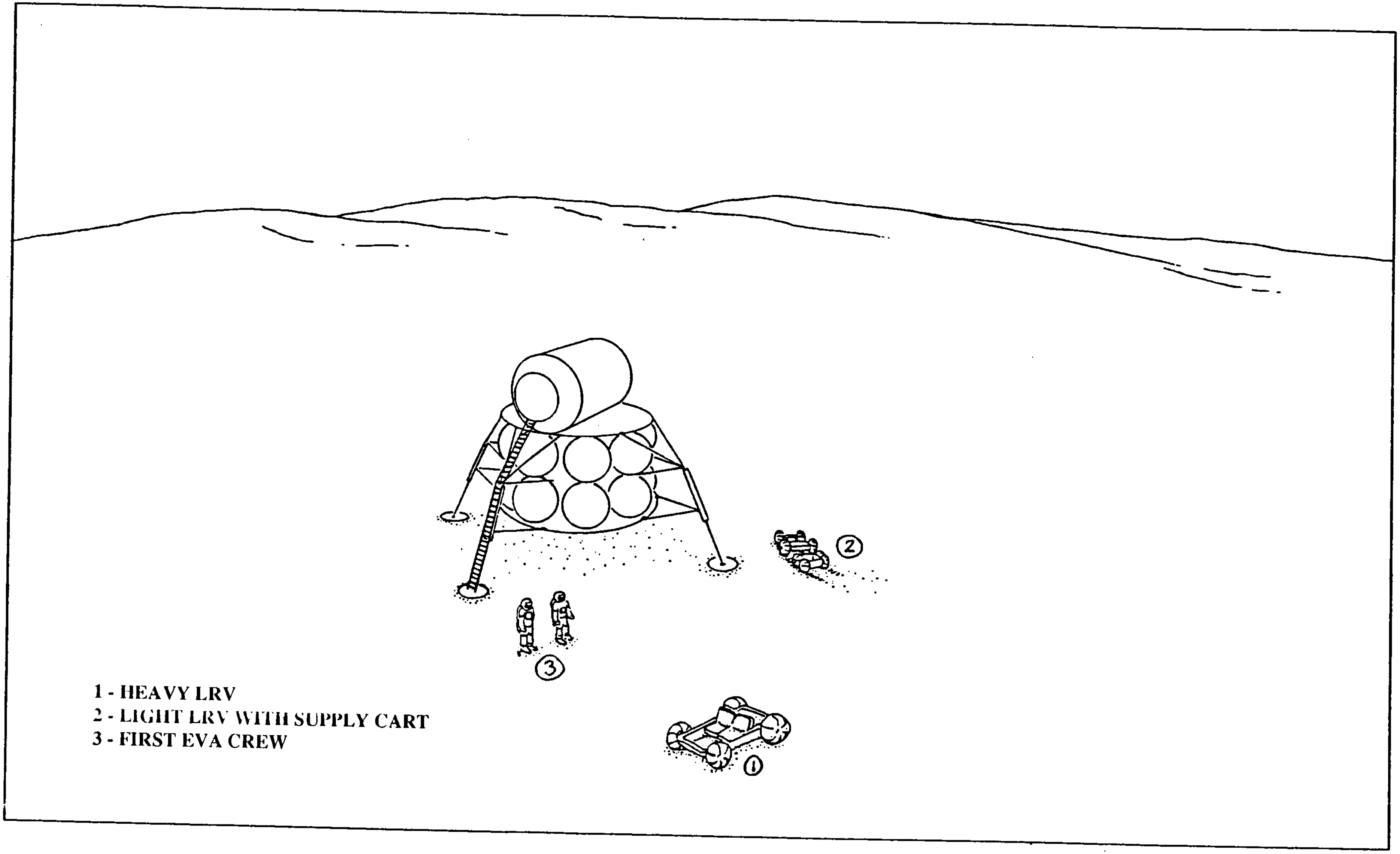

FIGURE 2: LRV'S ARE REMOTELY CALLED TO LANDER AND FIRST EVA CREW EXITS LANDER

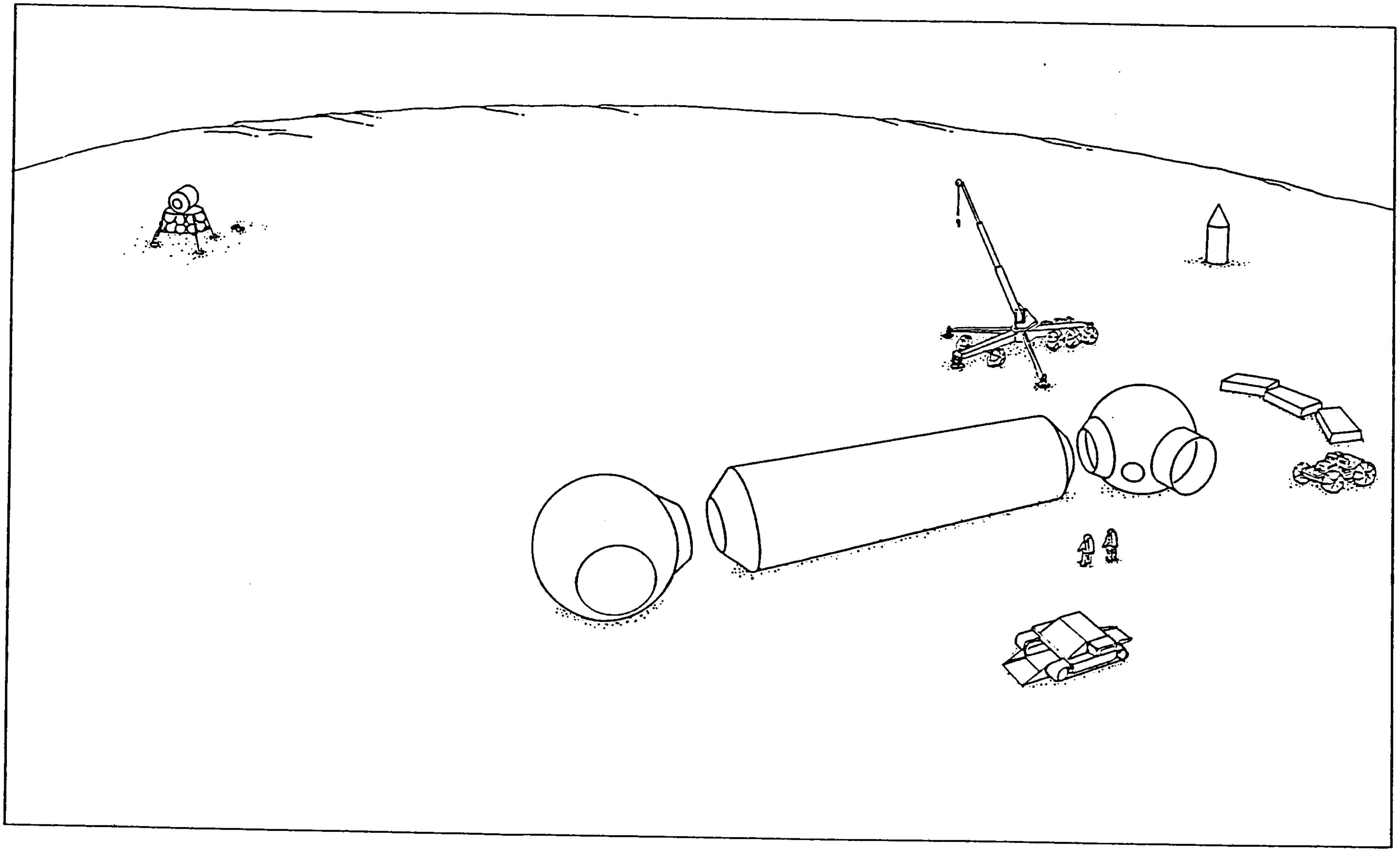

FIGURE 3: FIRST EVA CREW ARRIVES AT LUNAR BASE SITE

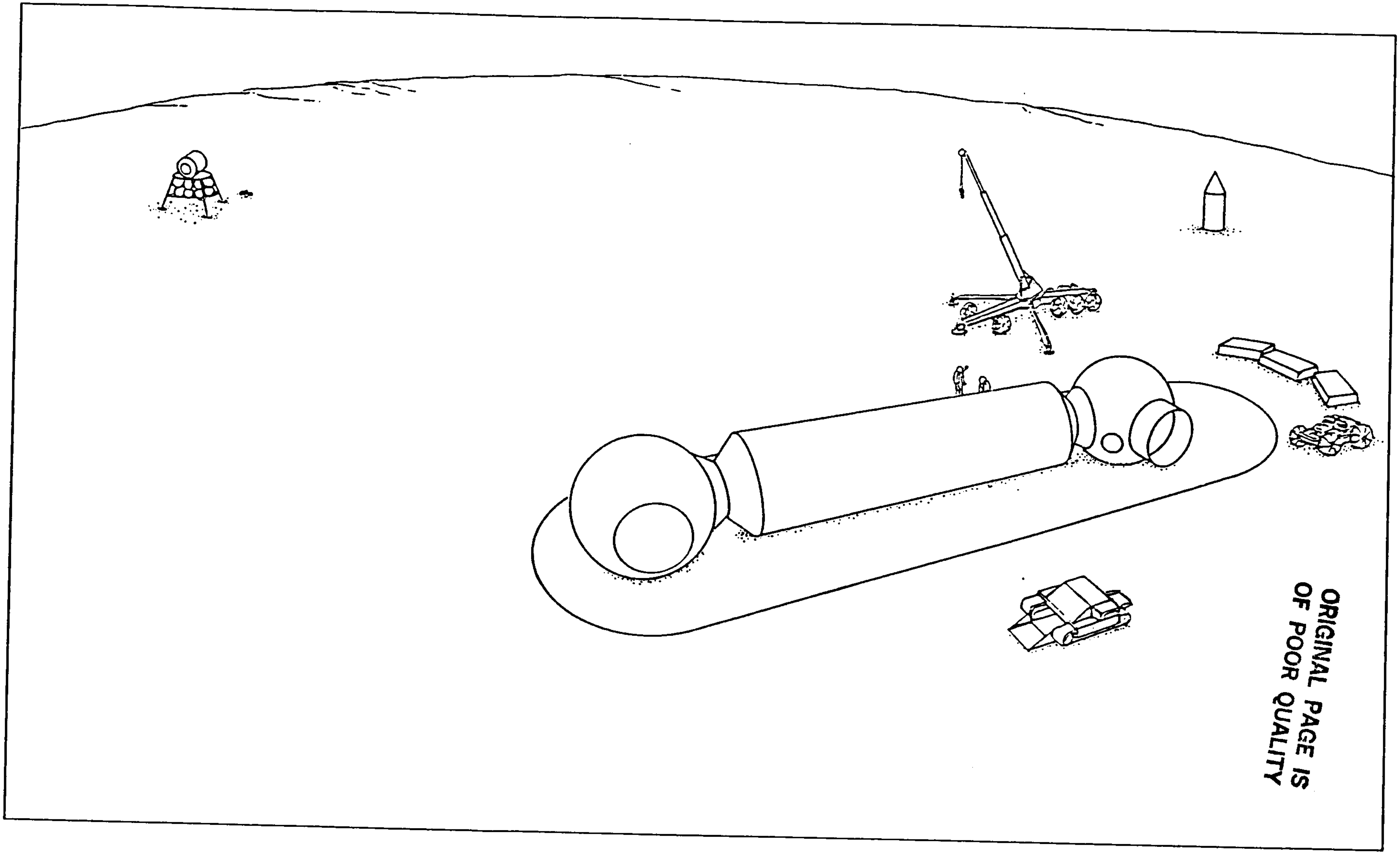

FIGURE 4: FIRST CREW PREPARES BASE AREA AND MATES MODULES

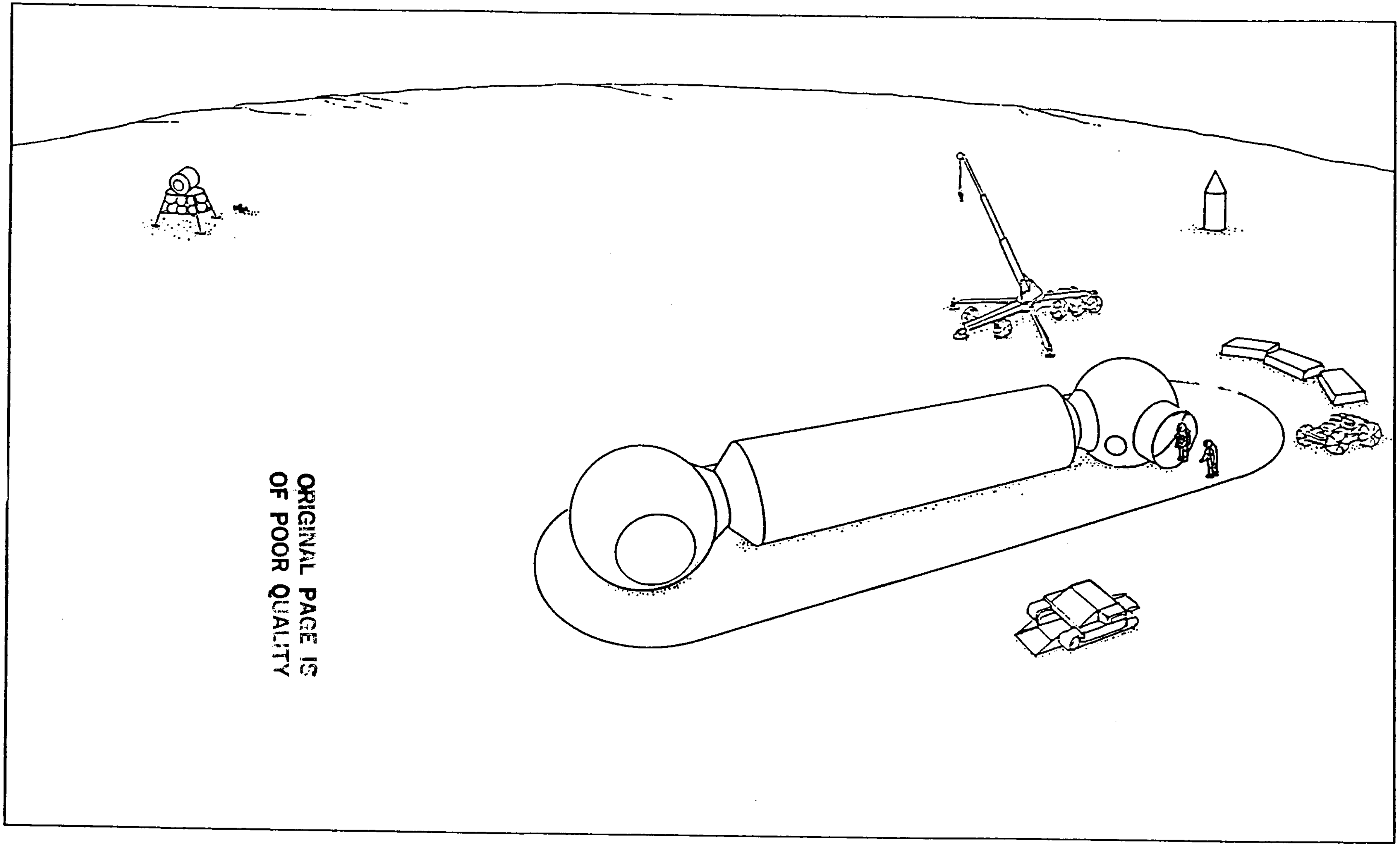

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FIGURE 5: FIRST CREW ENTERS HABITAT USING CREW AND EQUIPMENT LOCKS

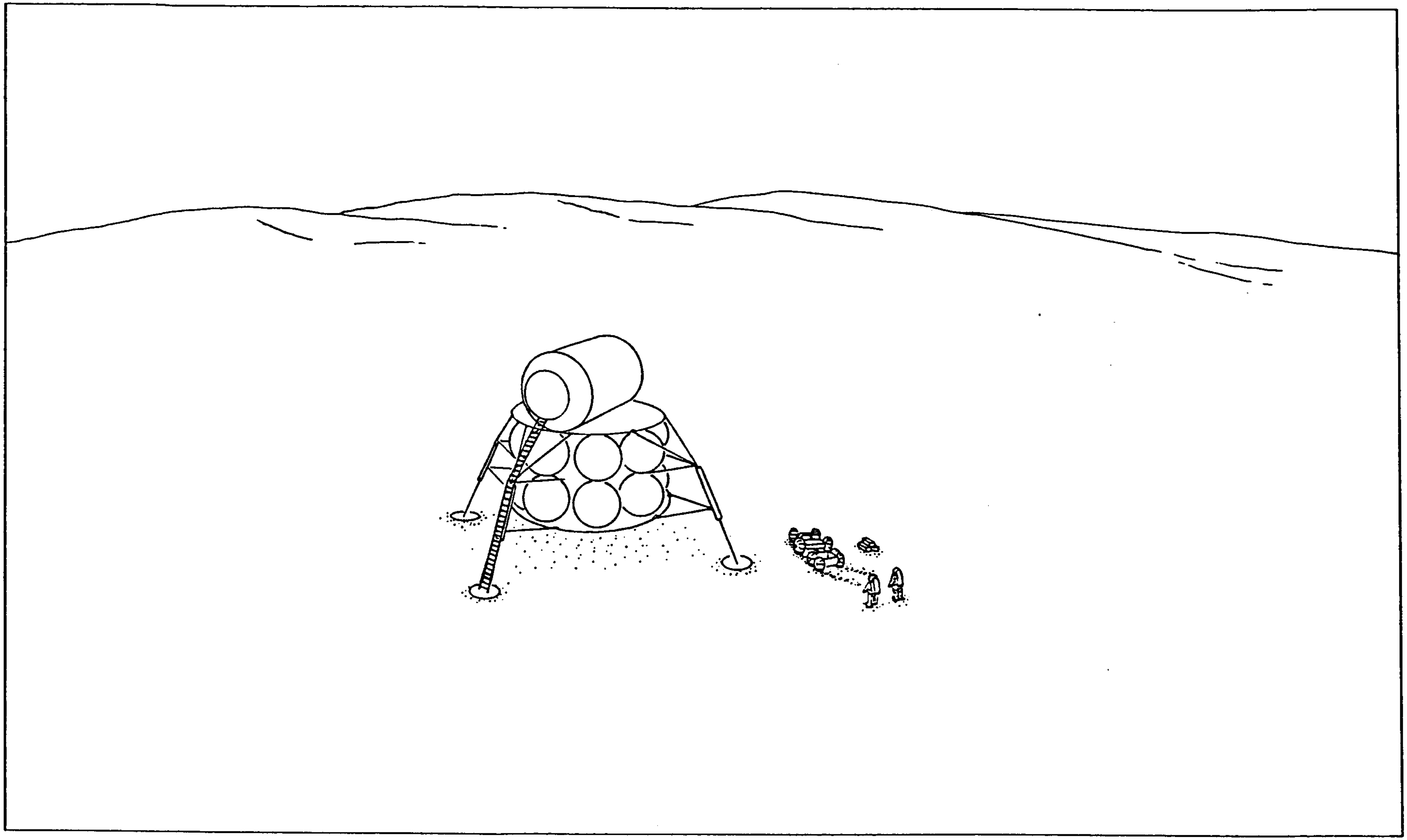

FIGURE 6: SECOND EVA CREW DESCENDS FROM LANDER

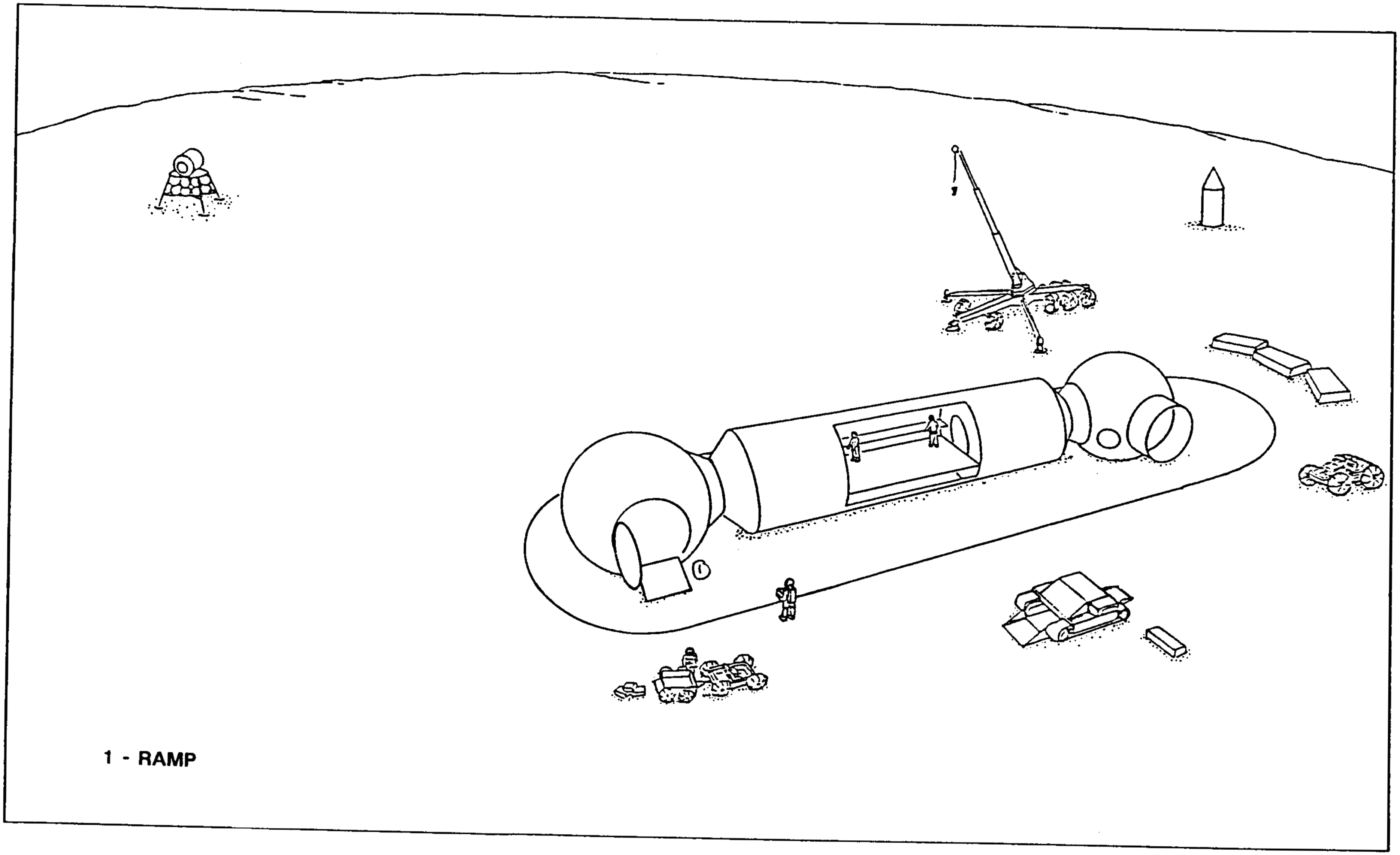

FIGURE 7: SECOND CREW TAKES ONE LOAD OF SUPPLIES AND USES LOGISTICS LOCK TO ENTER HABITAT

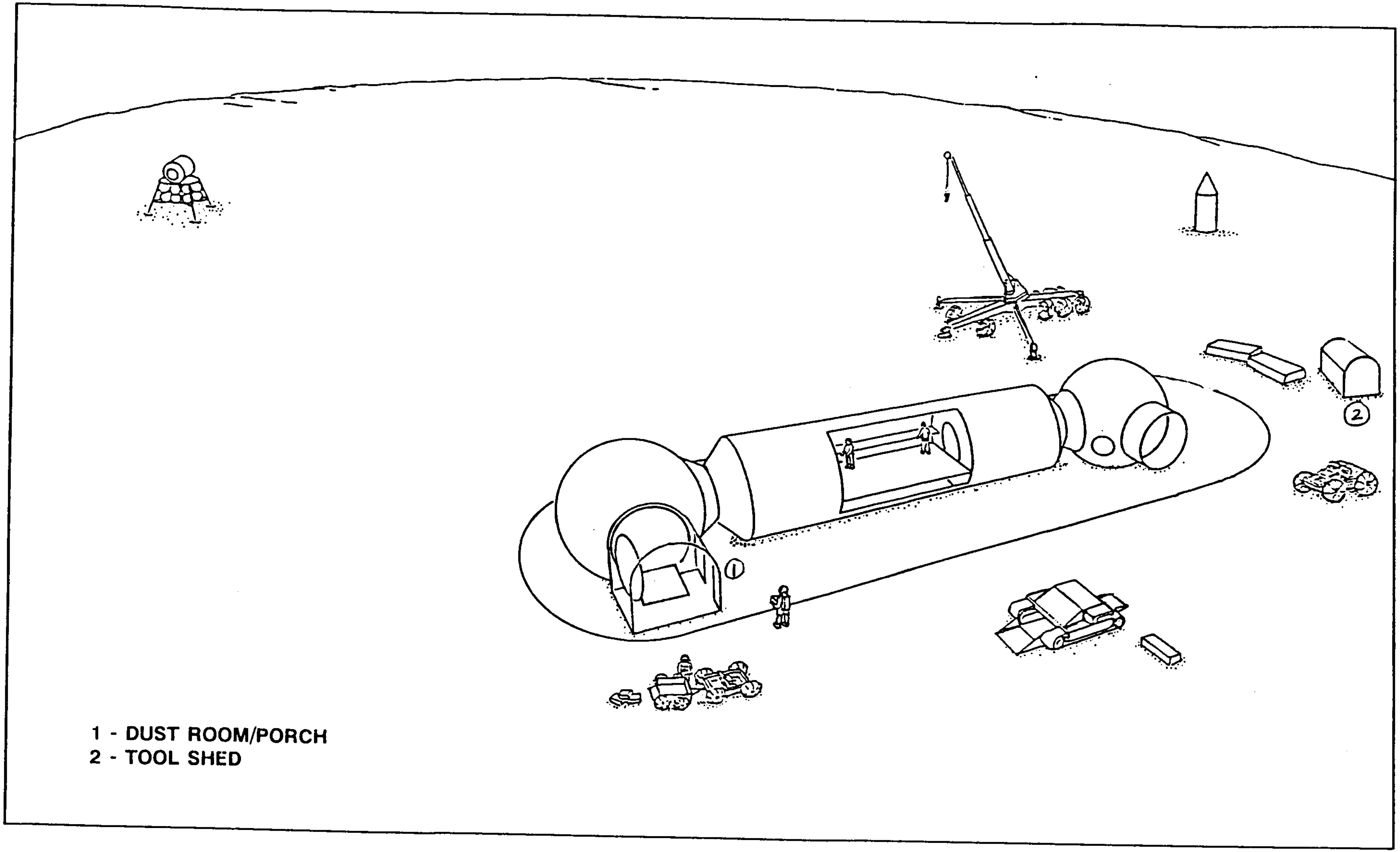

FIGURE 8: EVA CREWS TAKE TURNS CONSTRUCTING ANCILLARY STRUCTURES

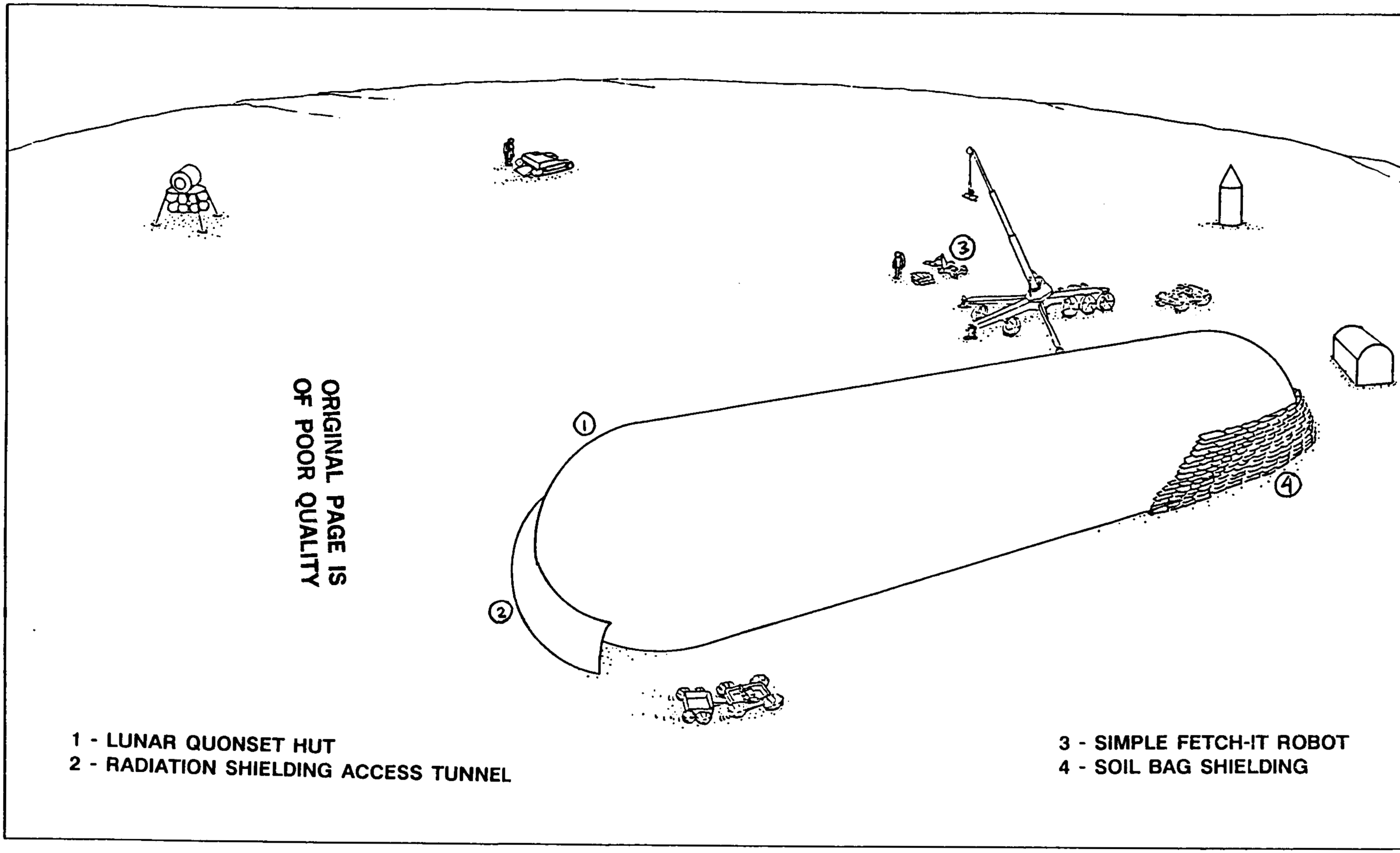

FIGURE 9: EVA CREWS TAKE TURNS CONSTRUCTING BASE SHIELDING

5.3 DRM Description

The DRM takes places some time around 2000-2005. Prior to this mission, numerous sortie-type missions will have been conducted to collect data required to select the lunar base site and to deliver and emplace equipment. This equipment will include a network of data-gathering sensors, instruments, and communications devices on the surface and in orbit, as well as all the elements shown in Figure 1. It is assumed that the DRM will be launched from a staging point in low-lunar orbit. This mannable transportation node could be a station in orbit or it could be a vehicle.

The DRM begins with the lander arriving on the lunar surface with four crewmembers inside (Figure 1). Prior to mission launch, all of the systems were remotely checked out. As the lander approaches touch down, the two LRV's are called from their storage locations to the landing site. Having this capability (to call the LRV's) gives greater flexibility and safety as a missed landing site will not require a long EVA to reach an LRV. In Figure 1 the airlocks and habitat are shown disassembled, but depending upon their size and weight, and the transportation systems available, these modules may arrive pre-assembled. EVA crews are assumed to consist of two crewmembers. Figure 2 shows the first EVA crew (Crew No. 1) exiting the lander and preparing to use the LRV to travel to the base site. The lander does not arrive at the base site because the dust, vibration, and other effects of the landing could be damaging to the equipment and modules. The distance will be a function of the speed of the LRV. It will enable the crew to reach a shielded facility in about 20 minutes. For example, at a LRV velocity of 9 km/hr the landing site can be at a distance of 3 km from the base site.

In Figure 3 Crew No. 1 has arrived at the base site and has begun the habitat checkout and initialization process. The tasks to be performed include preparation of the surface and leveling where the base will be located. Depending upon soil quality and density, some treatment may be required prior to emplacement of the modules. If the base comes pre-assembled, this task would have been part of one of the previous sortie missions. If the components arrive as shown in Figure 4, the crew will use the construction equipment (with interchangeable end-effectors) and an LRV (with attachments) to mate and emplace the modules. Figure 5 shows this operation completed and Crew No. 1 preparing to enter the equipment lock through the crew lock. This preparation will include cleaning of the Extravehicular Mobility Unit (EMU), stowing any tools which will not be brought inside, and removal and stowing of any EMU outer covers. The crew will then enter the equipment lock through the crew lock and perform system checkout for all of the habitat life support elements. Displays and controls for this function will be located in the crew lock and will be compatible with a suited crewmember to facilitate this operation. The airlock will then be pressurized and the hatch to the equipment lock and habitat opened. The crew will then perform a final checkout; and if all systems are nominal, they will doff their suits and enter the habitat.

Once Crew No. 1 has notified the remaining crew (Crew No. 2) in the lander that systems are nominal, Crew No. 2 will exit the lander and begin their EVA (Figure 6). They will take the second LRV and load it with items for the habitat and travel to the base site. Figure 7 shows Crew No. 2 taking their supplies and loading them into the logistics lock. After the supplies are loaded, they will clean off their suits, enter the logistics lock, perform checkouts, pressurize the airlock, doff their suits, and enter the habitat.

The remainder of the mission will be spent constructing ancillary structures such as the porches, tool shed, lunar quonset hut and access tunnels and constructing the shielding (Figures 8 and 9). These tasks assume the use of large construction equipment with interchangeable end-effectors, an automated bagging machine, and a simple fetch-it robot. The equipment would operate with crew supervisory control. It is possible that by the year 2005 the available technology would enable the entire shielding operation to be controlled by a single IVA crewperson at a supervisory control station. However, even if that were the nominal mode of operation, it would be important to understand the impact of manual or semi-automated operations on the EVA schedule and system requirements. Therefore, in this DRM one crewmember would be detailed to control the construction equipment and one to control the bagging equipment. Preferably, the site of soil collection should be

a short distance from the site of bag emplacement to minimize travel time. A simple fetch-it robot with an arm and end-effector will collect bags from the bagger, and transport them to the emplacement site. Using this scenario and making some assumptions about base design (see Appendix 1) and work cycles, it was calculated that the shielding operation would require 23 person days of EVA (with 6 hours EVA per crew and 2 EVAs per day). The performance of other additional tasks (depending upon work/rest cycles and EVA duration) would require a mission duration of 40 to 60 days.

6.0 LUNAR ENVIRONMENTAL CONSIDERATIONS

The most significant aspects of the lunar environment impacting AEVA were determined to be radiation, micrometeoroids, atmosphere, gravitation, illumination, lunar soil (dust), and the terrain itself).

6.1 Radiation

Three principal types of radiation are present on the lunar surface:

- Solar radiation, important primarily because of the effect of ultra-violet (UV) radiation on materials.
- Solar energetic particles (SEP's), important because of the high flux of these particles associated with solar flare events and the damage these particles can cause in human tissue.
- Galactic cosmic radiation (GCR), important because of the effects on humans of these very high energy particles and because of the effects of secondary neutrons when shielding is inadequate.

6.1.1 Solar Radiation

The flux of solar radiation (solar constant) incident on the lunar surface is 0.14 W/cm². Approximately 99% of the solar constant is accounted for by the spectral region above 3000 A, and the major portion of this energy is contained in the spectral region between 3000 A and 10,000 A. This spectral region includes UV radiation and the visible region.

Environmental Impact on Requirements

The intense UV radiation present in the lunar environment strongly degrades many polymeric materials. Materials for use in this environment must be resistant to deterioration as a result of exposure to UV. Protection for eyes against damage from the UV is also required.

6.1.2 Space Radiation Environment

Measurements of the radiation environment on the Moon are derived from the data from experiments performed on Earth and from science experiments on space missions.

The space radiation environment outside the Earth's upper atmosphere consists of SEP's and GCR. Figure 10 shows the flux density for the various SEPs and GCR as a function of particle energy and related this energy to the electron and proton range in aluminum and water. Based on these particle energy ranges, solar storm and solar flare protons and GCR are of primary interest.

6.1.2.1 SEP's

The sources of SEP's are occasional solar flare events which are transient releases of energy associated with active regions of the sun. Solar flare events inject large numbers of protons into the heliosphere. These particle have an average energy of about 100 MeV as compared with 1 GeV for the GCR, however, the SEP's exhibit a much larger flux density than GCR.

Solar flare events may occur as often as once every two months or as infrequently as once every two years. In the free-space environment, SEPs are of great concern because there is no safe haven although storm shelters may provide limited protection for average solar flare events. On the lunar surface, adequately protecting shelters, even from major solar flare events, is feasible. Figure 11 shows the proton fluence of three such events which typically have a duration of 16 hours. Figure 12 shows the dose equivalent for the August, 1972, SEP event. An event of this magnitude is projected to occur about once in 20 years. With a shielding thickness of 10 cm aluminum, the protection that is afforded will result in a total dose equivalent at 5 cm tissue depth of 40 rem. However, not even

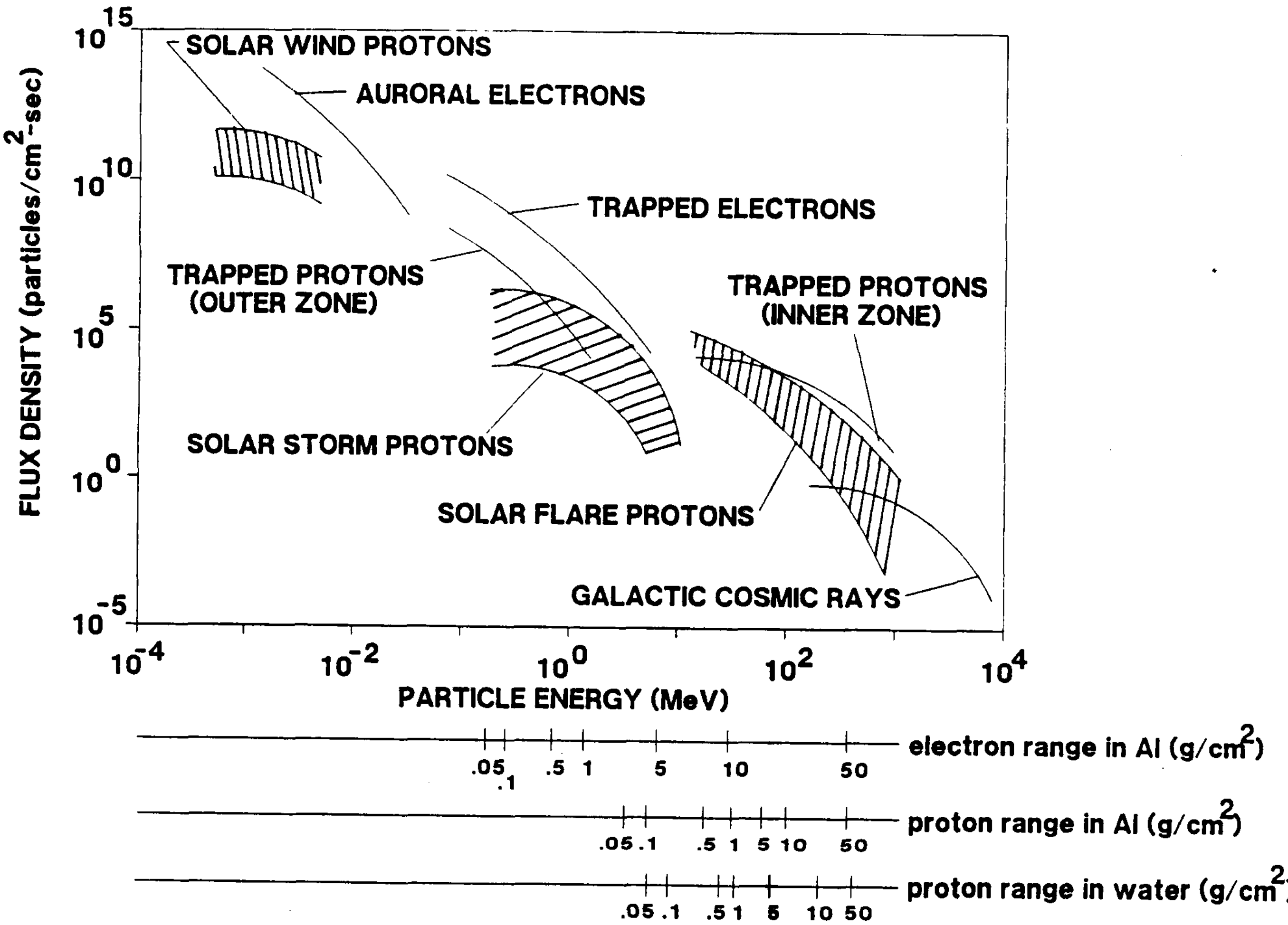

FIGURE 10: SPACE RADIATION ENVIRONMENT

Source: Wilson, J.W., "Environmental Geophysics and SPS Shielding," Workshop on the Space Radiation Environment. U.S. Department of Energy CONF-7809164, Dec. 1979 as modified by Nachtwev. NASA, Johnson Space Center, Feb., 1988.

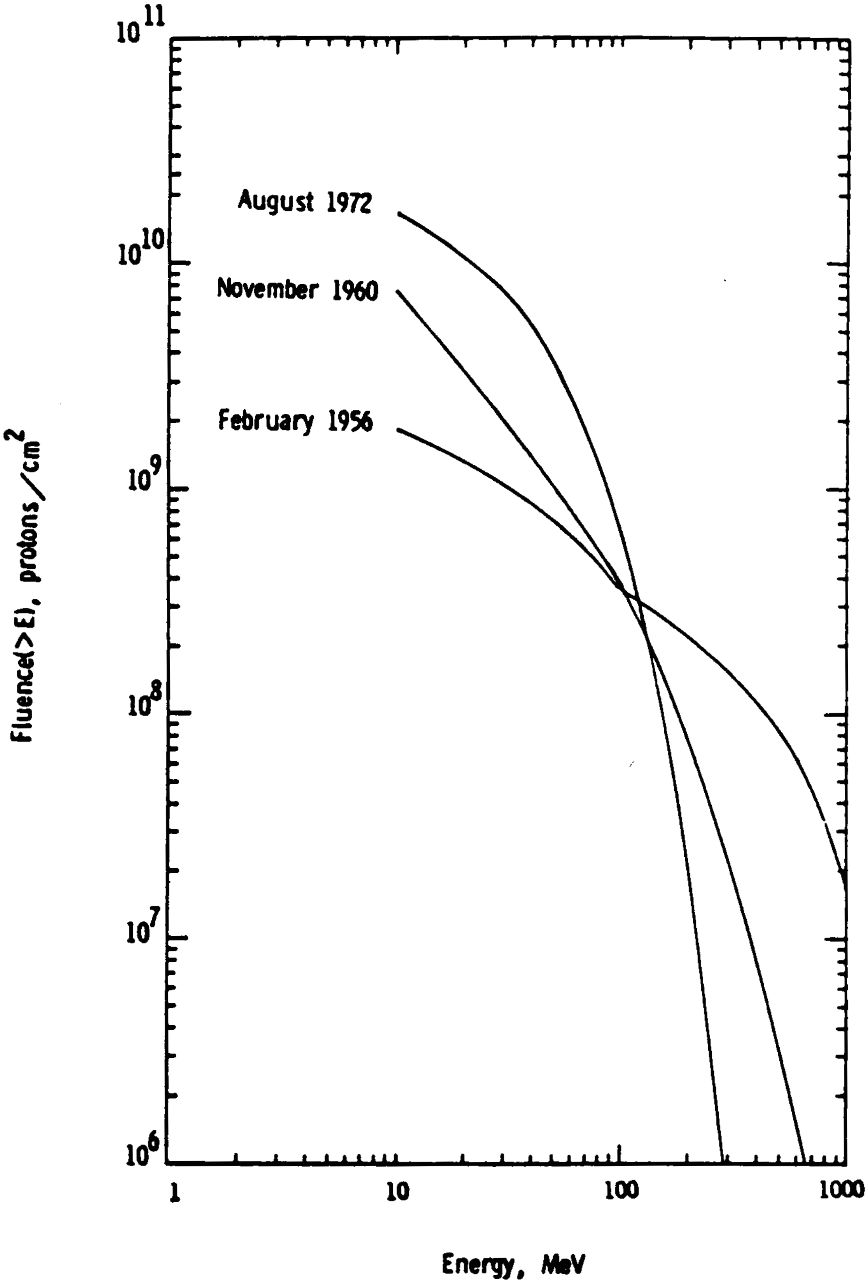

FIGURE 11: PROTON FLUENCE OF THREE MAJOR SOLAR EVENTS

Source: J.W. Wilson, ibid

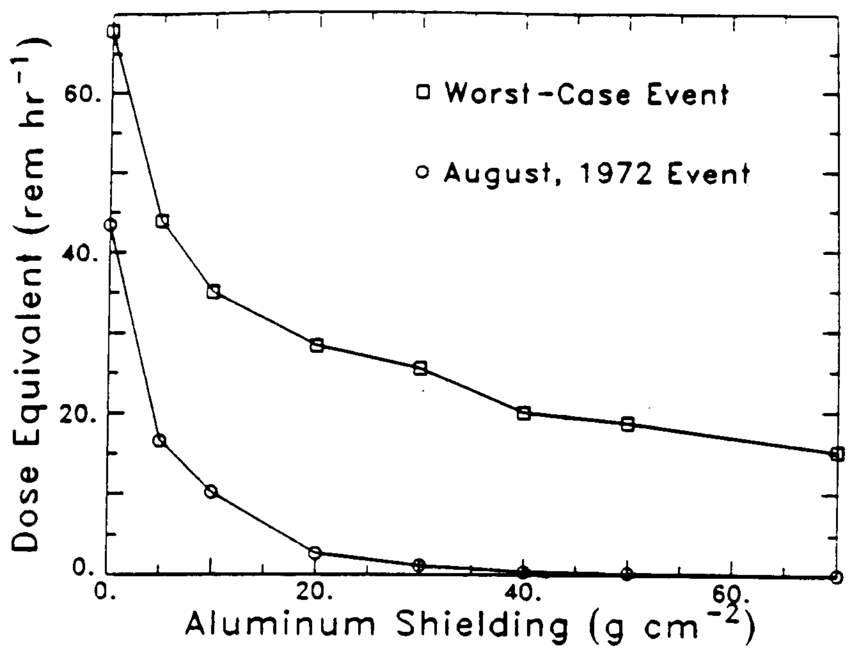

FIGURE 12: DOSE EQUIVALENT AT 5 CM TISSUE DEPTH VERSUS ALUMINUM SHIELDING THICKNESS FOR AUGUST, 1972 AND COMPOSITE WORST-CASE SOLAR ENERGETIC PARTICLE EVENTS

Source: Letaw, J.R.,; Silberberg, R.; and Tsao, C.H. "Radiation Hazards on Space Missions," Nature, v. 330 24/31, December 1987.

30 cm of aluminum under a conceivable but highly unlikely, worst-case event (see Figure 13) would prevent humans from receiving a disabling dose of 100 rem (See Table 1 for the recommended ionizing radiation exposure limits).

SEP's travel at a velocity less than the X-rays released from solar flares. X-rays would arrive at least 20 to 30 minutes and on average, about 90 minutes before SEP's arrive at the lunar surface. Detectors on the Solar X-Ray Imaging Satellite will provide at least 30 minutes warning of a solar flare event taking place.

Environmental Impact on Requirements

Because the effects of SEP's are potentially damaging to humans, shielding must be available on the lunar surface. Several meters of regolith or other available lunar materials are required for complete shielding.

6.1.2.2 GCR

GCR is a potentially prominent risk for extended EVA on the lunar surface. The radiation effects of GCR are caused by nuclei of all elements from hydrogen to uranium travelling at relativistic velocities. The flux of GCR is continuous; however the intensity varies inversely with solar activity over the 11 year solar cycle by about a factor of two.

The theory of physics of heavy-ion transport is well developed, although modeling of the complex interacting processes is only approximate. Generally it states that: nuclei of GCR are slowed down as a result of ionization losses, GCR primaries are fragmented as they interact in materials and continue to transport fragments (projectile secondaries), recoil neutrons are formed from proton and neutron collisions, and neutrons, protons and alphas (target secondaries) are produced in inelastic proton collisions.

The density of energy deposited by charged particles determines the absorbed radiation dose. For example, an iron nucleus creates a dense core of ionization in any material it passes through. Iron with $Z=26$ deposits ionization trails 676 times denser than protons ($Z=1$). High-energy iron nuclei deposit a dose in tissue which is 676 times greater than an equal number of minimum ionizing particles at a comparable energy.

The lunar surface is shielded from GCR over one hemisphere. Figure 13 shows the reductions in dose equivalent of radiation components at 5 cm tissue depth with increasing aluminum shielding thickness at solar minimum. Figure 14 shows the dose equivalent for solar minimum and solar maximum (GCR minimum) at 5 cm tissue depth with increasing aluminum shielding thickness. In this case shielding is much less effective although the overall dose is lower.

The annual dose equivalent on the surface of the Moon is about 25 rem or one-half of the dose equivalent in free space (Silverberg, et al, 1985).

Figure 15 shows the radiation dose and dose equivalent in lunar soil as a function of shielding. The local soil density will determine the depth of shielding required (see Section 7.1) A maximum radiation dose occurs at a depth (mass per unit surface area) of between 100 to 200/cm^2 as a result of secondary neutron particle generation. Only for depth where mass per unit surface area of available lunar surface material is greater than 400 g/cm^2 does the annual dose equivalent become smaller than 5 rem, the permissible annual dose for terrestrial workers exposed to a radiation environment. It should be noted that shielding of 700 g/cm^2 is required to achieve the permissible dose level for such workers if major solar flare events such as those shown in Figure 11 were to occur. At a shielding of 400 g/cm^2, a worker will receive a dose of 200 rem in 40 years which is the permissible lifetime dose for a few astronaut-volunteers.

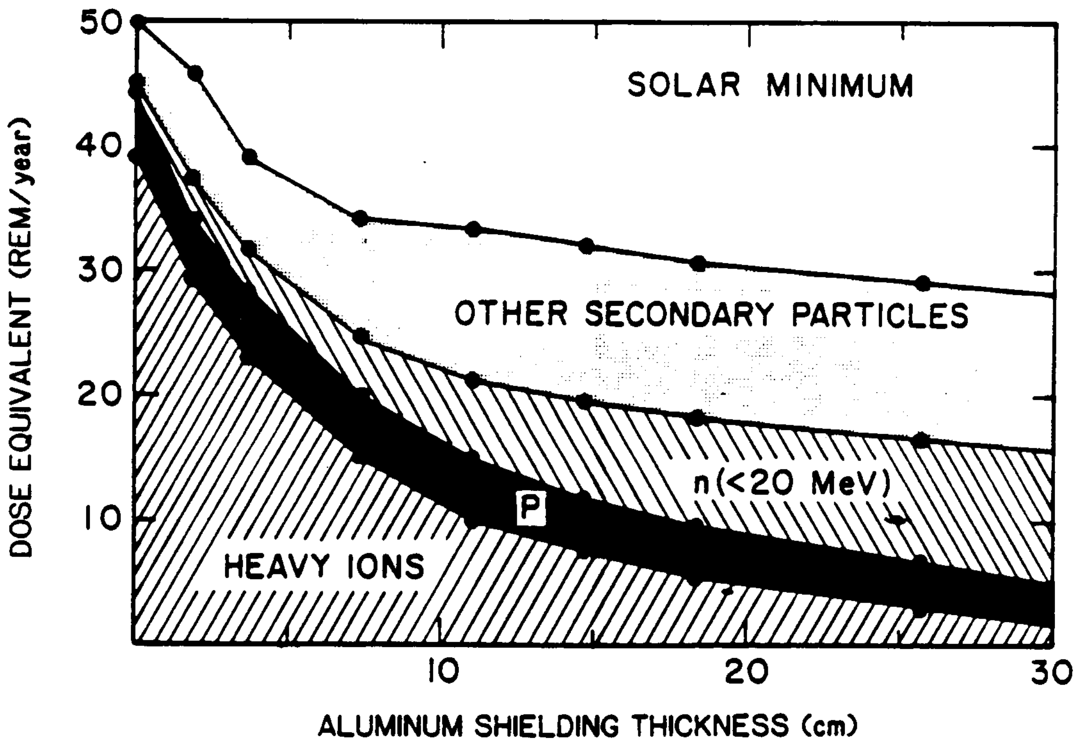

FIGURE 13: DOSE EQUIVALENT AT 5 CM TISSUE DEPTH VERSUS ALUMINUM SHIELDING THICKNESS AT SOLAR MINIMUM SHOWING RADIATION COMPONENTS INDIVIDUALLY

Source: J.R. Letaw, ibid

TABLE 1

RECOMMENDED IONIZING RADIATION EXPOSURE LIMITS

	Depth (5 cm)	Eye (0.3 cm)	Skin (0.001 cm)
30 Days	25 rem	100 rem	150 rem
Annual	50	200	300
Career	100-400	400	600

Notes

1. These does-equivalent limits have been recommended by the National Council on Radiation Received Measurement (NCRP) Scientific Committee No. 75 on Guidance on Radiation Received in Space Activities and are expected to be approved by NASA.
2. This table is expressed in conventional units common to usage by the discipline.
3. The career depth does-equivalent limit is based upon a maximum 3% lifetime risk of cancer mortality. The total dose-equivalent yielding this risk depends on sex and age at start of exposure. the career dose-equivalent limits is approximately equal to:

   200 + 7.5 (age - 30) rem's for males, up to 400 rem's maximum

   200 + 7.5 (age - 38) rem's for female, up to 400 rem's maximum

Source: Warren K. Sinclair, "Radiation Protection Standards in Space." Advances in Space Research, Vol. 6, No. 11, pp. 335-343, 1986.

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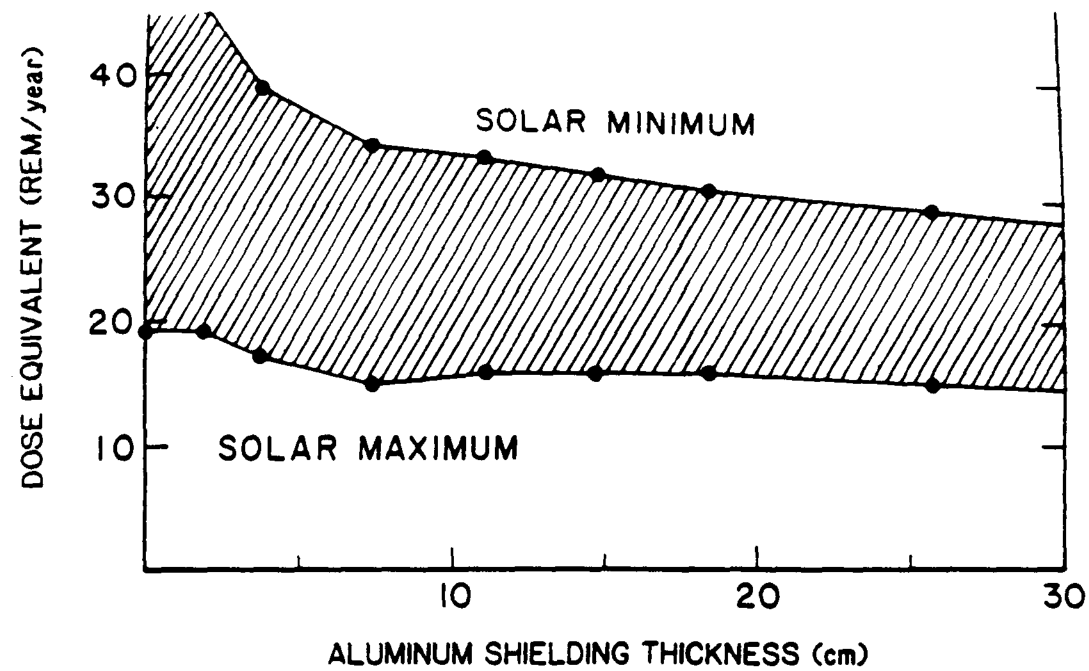

FIGURE 14: DOSE EQUIVALENT AT 5 CM TISSUE DEPTH VERSUS ALUMINUM SHIELDING THICKNESS AT SOLAR MINIMUM AND SOLAR MAXIMUM

Source: Letaw, J.R.; Silberberg, R.; and Tsao, C.H. "Radiation Hazards on Space Missions," Nature, v. 330 24/31, December 1987.

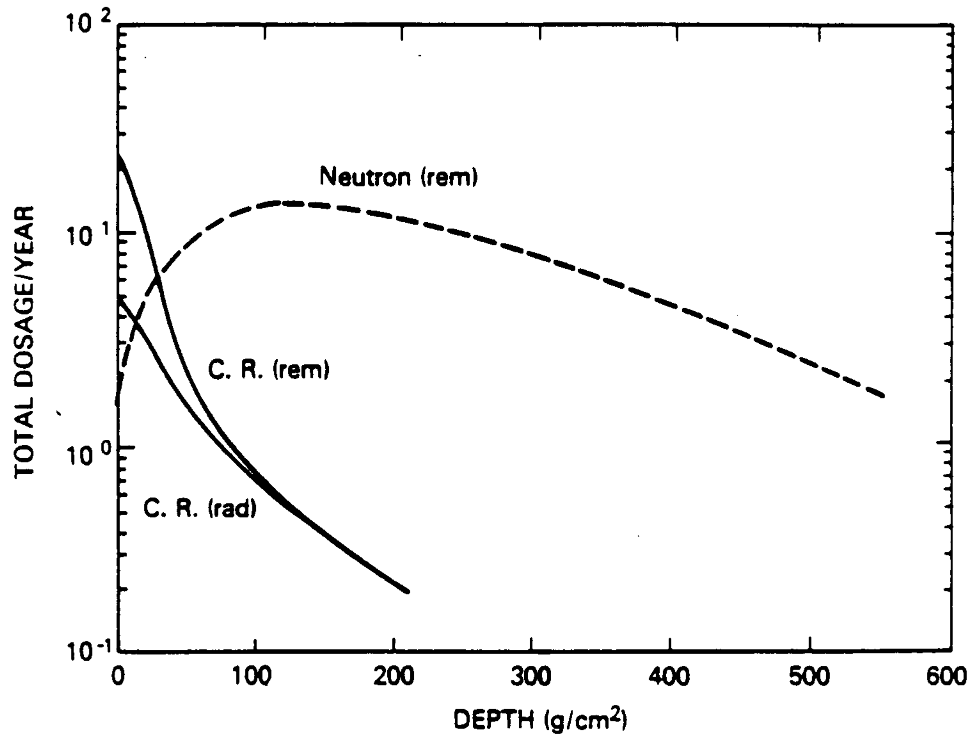

FIGURE 15: RADIATION DOSE AND DOSE EQUIVALENT AS A FUNCTION OF SHIELDING OF LUNAR SOIL

Source: Silberberg, R.; Tsao, C.H.; and Adams, J.H., Jr., "Radiaton Transport of Cosmic Ray Nuclei in Lunar Materials and Radiation Doses," in Lunar Bases and Space Activities of the 21st Century, Mendell, W.W., editor, Lunar and Planetary Institute, Houston, TX, 1985

Environmental Impact on Requirements

Long-duration residents on the Moon can spend about 20% of the time or 40% of the two-week daylight time without significant shielding (Silberberg). Most of the time should be spent in shelters provided with a shielding depth greater than 400 g/cm^2 or about two meters of densely packed lunar soil. At the time of rare gigantic solar flare events, shelters with a shielding depth greater than 700 g/cm^2 will be required. Although the risks of exposure to the space radiation environment are better understood, the recommended response limits (Table 1) are intended only for missions in LEO. For lunar surface EVA, the degree of radiation protection required may be in a different category when the missions are considered exploratory rather than for permanent residents.

It can be assumed that EVA missions will be performed without significant shielding. If 40% of the two-week daylight time can be spent in EVA, and 8 hours represent an EVA shift/day, then a crewmember could participate in EVA every day during this time for a total of 67.2 Earth days per year (i.e. 14 days at 40%, or 134.4 hours, or 16.8, 8-hour shifts during the 14 day period). EVA during the lunar night may be possible but should be reserved for critical operations or for EVA which can be performed in small, well-defined areas to reduce power consumption and equipment overhead.

6.2 Micrometeoroids

The surface of the moon is frequently struck by micrometeoroids with velocities ranging from 2.4 to 72 km/s. The mean velocity is about 20 km/s. The hazard to suited humans is small because most meteoroids are very small. The most frequent size ranges from 10^{-7} to 10^{-3} g. Micrometeoroids in the size range from 10^{-6} to 10^{-2} g contribute most of the energy. Micrometeoroids 10^{-4} to 10^{-3} g arriving at these velocities have a significant kinetic energy and are capable of causing biological or material damage. Meteoroids weighing from 100 g to 1000 kg impact the moon between 70 to 150 times per year. Each impact by even a small micrometeoroid will generate debris that will follow ballistic trajectories resulting in additional secondary ejecta. However, the lower velocity and smaller size of these ejecta, reduce the damage potential. More data is required to define the frequency and damage potential of micrometeoroids to a suited crewmember on the lunar surface.

Environmental Impact on Requirements

Garment protection against micrometeoroids appears to be adequate. The Apollo suits which had a nylon rip-stop/neoprene shell beneath the insulation were not penetrated during EVA excursions on the lunar surface. Spacesuit materials and painted surfaces may in time suffer degradation and require replacement or refurbishing. Incorporating protection in spacesuits against impact from meteoroids ($>10^{-3}$ g) is impractical. Instead, shelters covered by regolith or other lunar material will be used to provide protection from micrometeoroids.

6.3 Atmosphere

The atmosphere of the moon is a hard vacuum with the pressure of about 10^{-10} torr or less, with only traces of hydrogen, helium, neon and gases resulting from radioactive decay of lunar material.

Environmental Impact on Requirements

The absence of a lunar atmosphere (i.e., hard vacuum) is the most significant environmental factor determining human activities or the lunar surface. It exposes the lunar surface to the full spectrum of solar radiation and requires that space suits be designed to create a habitable environment during EVA.

6.4 Gravity

The gravitational attraction on the moon is about one-sixth of that on Earth. As a consequence, lifting of objects is much easier, the ballistic trajectory of an accelerated object is greatly extended, and locomotion is significantly affected. However, the moment of inertia of an object is the same as on Earth. Suited Apollo crewmembers adjusted rapidly to reduced gravity, as shown by NASA lunar video tapes of walking, striding and jumping. Interviews with crewmembers did not disclose any significant difficulties with suit mobility. However, they were not required to move heavy objects, because Apollo lunar science experiments were designed to be low mass, hand-carried and easily deployable. Crewmembers did not find a noticeable tendency for boots to slip on the surface (NASA SP-235, 1970, p. 31).

Environmental Impact on Requirements

The ability to move heavy objects along the lunar surface may be impeded by the granular nature of the lunar surface and the smaller downward force exerted against the lunar soil. Bulky and heavy objects, such as bags filled with regolith for shielding, may have an appreciable moment of inertia. However, underwater tests indicated that the learning curve for handling such material is steep, implying that crewmembers can quickly adjust to the change from Earth to lunar gravity.

6.5 Illumination

Because there is no atmosphere on the moon, the sun's radiation, corresponding to a radiating body of about 620°K, is not diffused.

Environmental Impact on Requirements

Objects are primarily illuminated directly, except for the small amount of light scattered by the material of the lunar surface. As a consequence, shadowed areas are very dark and may conceal hazards such as boulders or depressions. Interviews with crewmembers did not indicate that dark/light contrasts presented difficulties. However, the timing of Apollo missions was chosen to provide optimum illumination conditions. Shadows at lunar dawn and dusk may be more pronounced and require that artificial illumination be available to the crewmembers on the space suit or lunar surface.

Crewmembers noted that while going down-sun, there seemed to be a refraction halo around their bodies that caused a halo effect in their shadow, making it difficult to see surface details directly in front of them. Furthermore judgment of distance seemed distorted, and they tended to underestimate distances to terrain features (NASA SP-272, 1971 p. 35). Lighted areas are very bright (12,000 foot-candles solar illuminance at a mean solar distance) and filters are needed to protect human vision from glare.

6.6 Thermal Flux

The radiation to and from the surface of the moon is not moderated by the effects of an atmosphere, thus, heating and cooling by radiation occurs swiftly. Objects in direct sunlight during the day can attain surface temperatures of (111 °C (231.8°F) while objects radiating to deep space during the lunar night can reach a surface temperature of (-171 °C (-275°F). Thermal shock to materials resulting from these extremes of temperatures can be severe.

Environmental Impact on Requirements

Thermal control surfaces will be required to regulate the temperature within a space suit and in a habitat. Some surfaces may require active control of their emissivity. Active thermal control for the space suit is provided by the PLSS and by an ECLSS for the habitat. Specific tasks such as regolith bagging operations may generate dust that could deposit itself on the PLSS thermal control surfaces thus changing their properties. Micrometeoroids may degrade surface emissivity thus, cleaning may be required or an emissivity regeneration method may need to be developed.

7.0 GEOTECHNICAL CONSIDERATIONS

7.1 Lunar Soil

The surface of the moon differs significantly from terrestrial soil because of the absence of terrestrial geological processes which produce well-sorted sediments. The range of geotechnical properties of the lunar surface are less than occur on Earth because a large portion of the soil is glass-like (Figure 16 shows a sample of Apollo lunar soil). The most significant variable is the relative density caused by differences in specific gravity, particle shape, size distribution, and different geologic sources, and processes. Meteoroid impacts are the primary lunar soil-forming processes which strike, erode, and fracture soil particles and produce well-graded soil resulting in a narrow range of particle distribution. The median particle size is 40 to 130 microns with an average of 70 microns. Fines smaller than 20 microns constitute 10 to 20% of the soil. A thin layer of dust adheres to every object that comes into contact with the soil because of electrical charge, vacuum adhesion and low gravity. The dust particles are easily dislodged and rise in a cloud when disturbed, with each particle following a ballistic trajectory. They are of extremely irregular, reentrant shapes (forming interior cavities with outer surfaces twisting inward), abrasive, and scratch optical surfaces such as windows, visors, lenses, mirrors and thermal coatings when attempts are made to remove them. When a significant horizontal velocity is imparted to the particles (e.g. during launch operations), they can travel considerable distances and may cause deterioration of exposed surfaces akin to sand-blasting.

The average specific gravity of lunar soil is related to the relative proportions of particle types and their origin (i.e., basalts, mineral fragments, breccias, agglutimates and glasses).

The specific gravity range was found by Duke, et al (1970) to be as follows:

Particles	Specific Gravity (g/cm^3)
Agglutimates and Glass	1.0 to >3.32
Basalt	>3.32
Breccia	2.9 to 3.1

Based on measurements of in situ bulk density of the regolith obtained from Apollo core tube samples, the average bulk density of the top 15 cm of lunar soil is 1.50 ± 0.05 g/cm^3, and of the top 50 cm, 1.66 ± 0.05 g/cm^3 (Mitchell, et al, 1974). The density is highly variable, from site-to-site, station-to-station, and with depth. The density increases from the surface to a depth of 70 cm; below that depth, the density profile is erratic.

Of interest is the experience of Apollo crewmembers emplacing the heat flow experiment with the lunar drill. They reported unexpected resistance of the regolith to drill penetration and also that collection of the deep core sample was extremely difficult, physically exhausting, and far more time consuming than anticipated (NASA SP-289, 1972, p. 4-2).

The best estimate of bulk density is given by Mitchell, et al (1974) and is as follows:

Average Bulk Density (g/cm3)	Depth Range (cm)
1.50 ± 0.05	0-15
1.50 ± 0.05	0-30
1.74 ± 0.05	30-60
1.66 ± 0.05	0-60

Lunar microwave emission data (Keihm and Langseth, 1975) indicated that the lunar soil layer over a large portion of the moon may be 10 to 30 m thick.

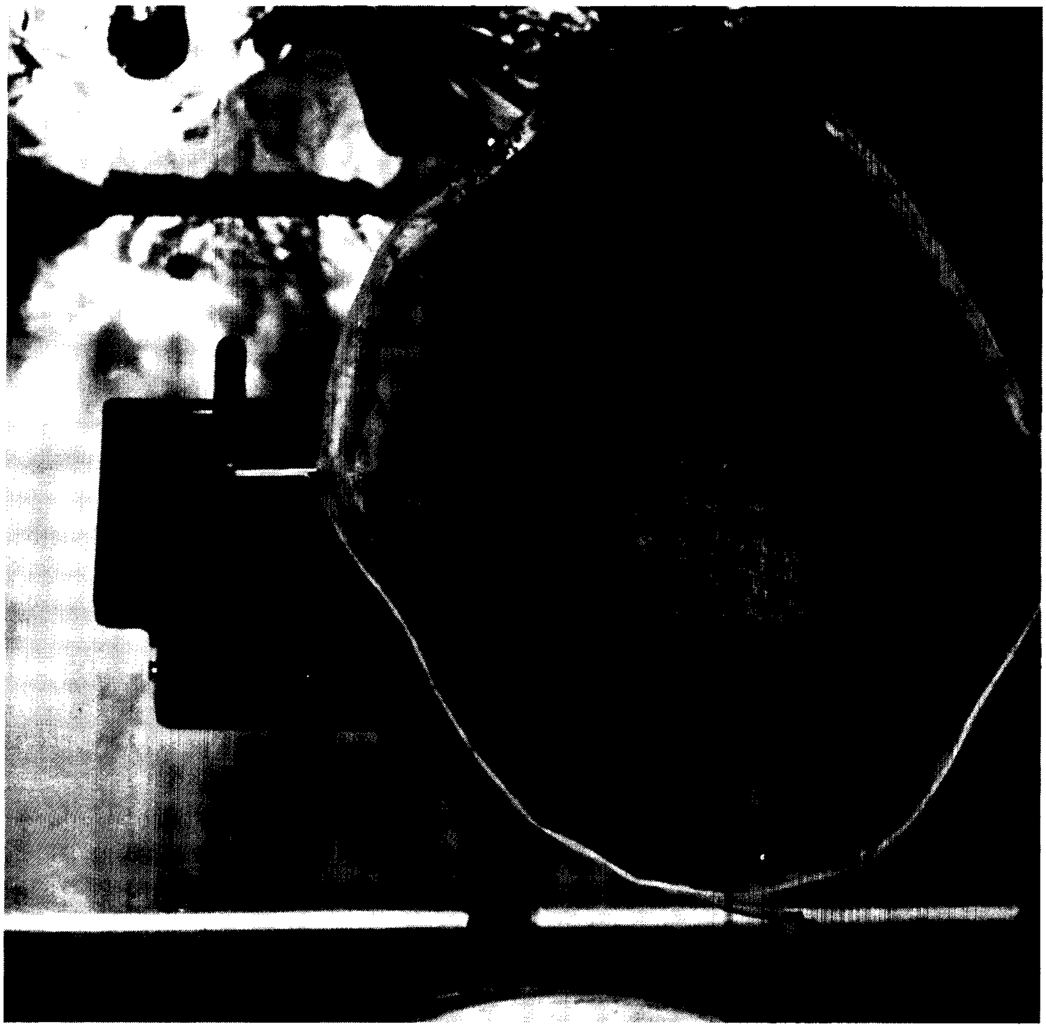

FIGURE 16: APOLLO LUNAR SOIL SAMPLE

The relative density of lunar soil based on measurements of penetration resistance from the Russian Lunokhod and from Apollo missions 14-16 indicated that the relative density tends to be low on the rims of fresh craters, on slopes, and within the top few centimeters of the surface over large areas, but the relative density is exceptionally high just 5 to 10 cm deep in the intercrater areas.

Best estimates of relative density versus depth (Mitchell, et al, 1974 and Houston, et al, 1974) are as follows:

Depth Range (cm)	Relative Density (%)	Description
0-15	65 ± 3	Medium to Dense
0-30	74 ± 3	Dense
30-60	92 ± 3	Very Dense
0-60	83 ± 3	Dense

In order to account for the change in relative density that occurs in the top 30 cm of lunar soil, it is assumed that meteoroid impacts stir up the surface and densify the underlying soil.

The shear strength of a granular soil consists of a cohesive and a frictional component. Based on a variety of data sources Mitchell, et al (1972 and 1974) have developed the following model of lunar soil shear strength:

Cohesion: 0.1 to 1 kPa
Friction angle: 30° to 50°

The allowable bearing capacity of lunar soil is controlled by its compressibility and the acceptable amount of settlement for a given structure. For a load applied directly on the lunar surface and a footing width less than about 0.5 m, (e.g. based on the crewmember bootprints such as those seen in Figure 17), depth of bootprint and crewmember mass, the modulus of subgrade reaction, k, can be calculated statistically (see Figure 18). The allowable bearing capacity, Q_{all} is given by:

$$Q_{all} = k\, d_{acc}$$

where d_{acc} = acceptable settlement

Although the ultimate bearing capacity of the soil will depend on footing width, (e.g., about 500 kPa for a width of 20 cm) the allowable bearing capacity is significantly less. If the average modulus of subgrade reaction is 8 kPa/cm for a LRV wheel and the acceptable settlement depth is 1 cm, then the allowable bearing capacity is 8 kPa. For the design of a foundation with a 95% confidence level, a modulus of subgrade reaction of 2 kPa/cm should be used. For a settlement-sensitive structure spread footings (such as those on the LEM) at a depth of at least 30-100 cm should be used to reach below the depth of diurnal temperature fluctuations of the soil. If a soil-supported structure contains rotating machinery, the resonance frequency will be less than for a similar structure on Earth and should be avoided to eliminate undesirable vibrations.

If an excavation is required, a vertical cut could be made in the lunar soil to a depth of about 3 meters. A slope of 60° could be maintained to a depth of 10 meters.

Limited penetrometer data indicates that soil stability on slopes is less than in intercrater areas at least to a depth of 70 cm. Slope failures, possibly caused by meteoroid impacts, have occurred on the lunar surface. In some cases, the talus material (i.e., a pile of rock debris at the foot of a crater), has covered large areas and traveled many kilometers.

Lunar slope degradation may be caused by outgassing due to shearing of lunar soil in the impact zone leading to fluidized conditions and resulting in large distances for debris spreading. At present, many questions regarding the stability of natural slopes remain unresolved.

FIGURE 17: APOLLO ASTRONAUT BOOTPRINTS ON LUNAR SURFACE

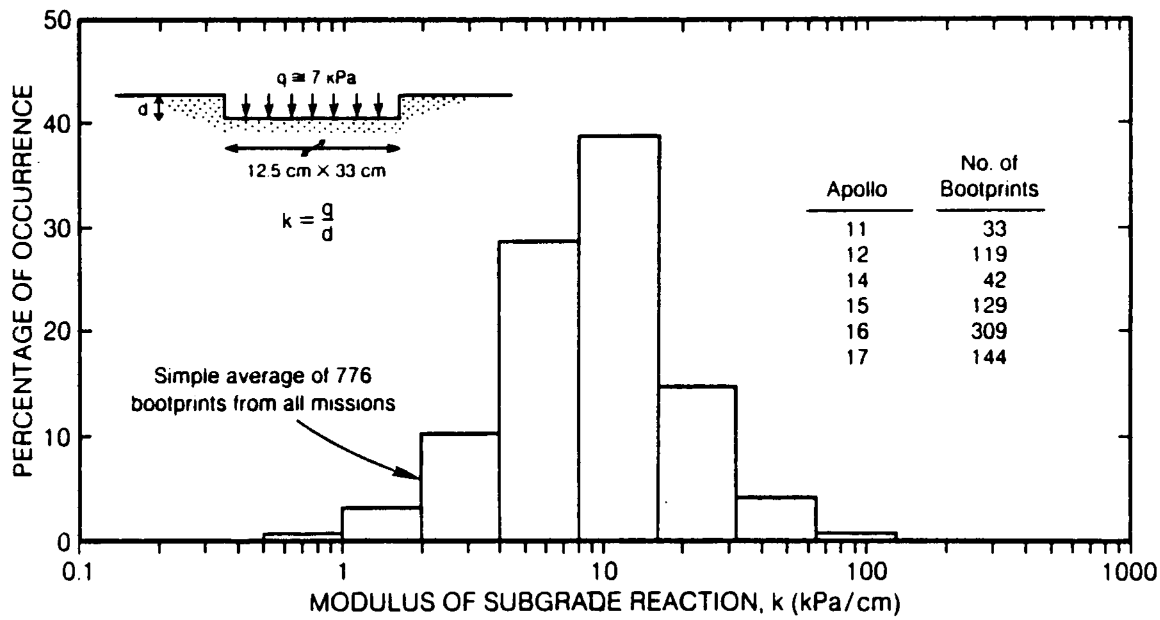

FIGURE 18: STATISTICS OF BOOTPRINTS AND ASSOCIATED MODULUS OF SUBGRADE REACTION

Source: Heiken, G. and Vaniman, D., editors, Lunar Source Book, Chapter 9, Cambridge University Press, Cambridge, England, 1988, (in press).

The trafficability of lunar soils by LRV's (i.e. capacity of the surface to withstand movement of the LRV) is reasonably well established. Wheel-slip on the lunar surface was measured to be 2% to 3% which allowed for accurate navigation by dead-reckoning. The maximum speed on a smooth level surface was about 13 km/hr. However, to avoid small craters with rounded rims, the cruise speed was about 6 to 7 km/hr. Hard turns at speeds above 5 km/hr resulted in skidding. The maximum negotiable slope was 19° to 23°. The energy consumption of the LRV (average "mileage"), was 35 to 36 W-hr/km or 0.050 to 0.080 W-hr/km/kg of electrical power.

Geotechnical Impact on Requirements

A layer of fine dust particles cover the lunar surface. These particles adhere to every object and are a major challenge to achieving future mission and EVA goals (Figure 19 shows an Apollo EVA crewman covered in lunar dust). For example, dust penetration into bearings could interfere with suit mobility, deteriorate thermal control surface performance, and abrade optical surfaces as a result of attempted cleaning.

The limited bearing capacity of lunar soil will require that spread footings be employed for settlement-sensitive structures. Mining of regolith as a shielding material for a habitat or shelter can be done to a depth of about 10 m while maintaining a slope of 60°

7.2 Terrain

The ability of the lunar surface to support a bearing load varies significantly. Local conditions must be evaluated before any structures are erected or paths for LRV's established (NASA TM-82487, p. 3-24).

Craters on the lunar surface range widely in size, from the largest that are hundreds of km across and several km deep to the smallest that are microscopic in size. They were formed by impacting meteors (Taylor, 1975). The larger and older craters ranging in diameter from hundreds of km across to several km deep have often been partially filled with lava, giving them a relatively smooth surface. The ratio of depth to diameter varies from 0.25 to 0.11 (NASA TM-64627, p. 4-24). The number of craters of a particular size is inversely and exponentially related to the diameter of the crater (NASA TM-82487, pp. 3-16/3-14).

The roughness of the lunar surface varies considerably. About 19% of the surface is relatively smooth, with the underlying bedrock covered by 3 to 16 meters of fragmented rock known as regolith. These areas are called the maria. The other 83% of the surface, known as the highlands or uplands, has a higher elevation and is rough and densely cratered. The depth of the regolith in the highland areas varies upward from 10 meters (NASA TM-82487, pp. 3-8/3-13). In both the maria and the uplands, boulders will be found that will prevent the passage of vehicles.

The bearing characteristics of the local surface will be important since bearing strength can vary from 0.02 N/cm^2 (4.2 lb/ft^2) to as much as 100 N/cm^2 (20,000 lb/ft^2)(NASA TM 82487, p. 3-24).

Geotechnical Impact on Requirements

The location of the habitat has to be chosen based on the capability of local conditions to support bearing loads. The route followed by LRV's must be laid out to ensure that loads can be transported safely over varied terrain avoiding rough and densely cratered areas and traveling only on permissible slope angles.

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FIGURE 19: APOLLO CREWMAN COATED IN DUST

8.0 EVA HARDWARE DESIGN AND INTERFACE ACCOMMODATIONS REQUIREMENTS

The mission and environmental descriptions provided a framework for developing the AEVA requirements. The requirements were the result of the relationship and trade-offs among that framework, human life support needs, and EVA productivity goals. This process was iterative and incorporated information from many knowledgeable sources at NASA, TAG members, and study team members. These requirements are complex, detailed and interrelated. To present these requirements logically and concisely they are divided into the following four categories.

- Mission Operations Requirements,
- EVA Man/Machine and Physiological/Medical Requirements,
- EVA Hardware Requirements, and
- EVA Hardware Interface Accommodations Requirements.

Within each category the requirements are subdivided into areas corresponding to those delineated in the NASA SOW. They are listed by section number and corresponding SOW number in Table 2. Each section discusses the requirements, their rationale, and any supporting data that is relevant. If these supporting data are too voluminous to include, reference is made to their sources.

In order to make the requirements as useful and specific as possible, a wide variety of trade-off analyses were conducted which take a global requirement and make it compatible with other global requirements. The result is a specific requirement which is physiologically acceptable, consistent with operational requirements, and feasible to implement.

TABLE 2

ORGANIZATION OF EVA HARDWARE DESIGN AND HARDWARE INTERFACE ACCOMMODATIONS REQUIREMENTS COMPARED TO SCOPE OF WORK

Report Section		Corresponding Study SOW Par.
8.1	Mission Operations Requirements	3.2.1
8.1.1	EVA Scenario Definition	3.2.1.1
8.1.2	EVA Workday Length	3.2.1.2
8.1.3	EVA Work Period Parameters	3.2.1.3
8.1.4	EVA Duration Optimization	3.2.1.4
8.1.5	EVA Translation Considerations	3.2.1.5
8.1.6	EVA Rescue Capability	3.2.1.6
8.1.7	Anthropomorphic Sizing Accommodation	3.2.1.7
8.1.8	Logistics	3.2.1.8
8.1.9	Maintainability	3.2.1.9
8.1.10	EVA Hardware Servicing	3.2.1.10
8.1.11	Cleaning and Drying	3.2.1.11
8.1.12	Caution, Warning, and Checkout	3.2.1.12
8.1.13	Communication Requirements During EVA	3.2.1.13
8.1.14	Contamination Prevention/Waste Disposal	3.2.1.14
8.2	EVA Man/Machine and Physiological/Medical Requirements	3.2.2
8.2.1	EVA Duration	3.2.2.1
8.2.2	EVA Duty Cycles	3.2.2.2
8.2.3	Dimensional Limits	3.2.2.3
8.2.4	Unique Human Capabilities	3.2.2.4
8.2.5	Metabolic Profiles	3.2.2.5
8.2.6	Carbon Dioxide	3.2.2.6
8.2.7	Thermal Storage of Body Heat	3.2.2.7
8.2.8	Audio Level Quality Range and Warnings	3.2.2.8
8.2.9	Visual Displays and Warnings	3.2.2.9
8.2.10	Perception of Surrounding Environment	3.2.2.10
8.2.11	Toxicity	3.2.2.11
8.2.12	Radiation Tolerance	3.2.2.12
8.2.13	Personal Hygiene	3.2.2.13
8.2.14	Waste Management/Containment	3.2.2.14
8.2.15	Food Water	3.2.2.15
8.2.16	Medical Care/Facilities	3.2.2.16
8.2.17	Atmosphere Composition/Pressure	3.2.2.17
8.2.18	Suit Pressure	3.2.2.18
8.2.19	Biomed Data-Monitoring and Management	3.2.2.19
8.2.20	Medical	3.2.2.20

TABLE 2 (Continued)

ORGANIZATION OF EVA HARDWARE DESIGN AND HARDWARE INTERFACE ACCOMMODATIONS REQUIREMENTS COMPARED TO SCOPE OF WORK

Report Section		Corresponding Study SOW Par.
8.3	EVA Hardware Requirement	3.2.3
8.3.1	Design Loads, Operating Life, and Safety Factors	3.2.3.1
8.3.2	EVA Tools	3.2.3.2
8.3.3	Restraints/Workstations	3.2.3.3
8.3.4	Communications	3.2.3.4
8.3.5	Crewmember Translation	3.2.3.5
8.3.6	Propulsion System Assessment	3.2.3.6
8.3.7	External Configuration	3.2.3.7
8.3.8	Thermal Environment	3.2.3.8
8.3.9	EVA Rescue Requirements	3.2.3.9
8.3.10	EVA Operational Life	3.2.3.10
8.3.11	EVA Worksite	3.2.3.11
8.3.12	Cut/Penetration/Abrasion	3.2.3.12
8.3.13	Micrometeroid/Space Debris Penetration	3.2.3.13
8.3.14	Sand/Dust and Surface Terrain Conditions	3.2.3.14
8.3.15	Radiation Environment	3.2.3.15
8.4	Hardware Interface Accommodations Requirements	3.3
8.4.1	Communications	3.3.1
8.4.2	Logistics	3.3.2
8.4.3	Safe Haven and Portable Shelter	3.3.3
8.4.4	Crewmember Autonomy	3.3.4
8.4.5	Dedicated EVA Hardware Servicing Area	3.3.5
8.4.6	Airlock Interfaces	3.3.6
8.4.7	Transportation	none
8.4.8	Other	none

8.1 Mission Operations Requirements

Mission Operations Requirements are those factors which define the constraints under which an EVA crewmember must operate.

8.1.1 EVA Scenario Definition

The scenario is defined by the activities which must be accomplished in accordance with the overall mission goals. As described above, the DRM's goal is to initialize a manned lunar outpost. The nominal operations required to achieve the mission goals include:

Vehicle/Module Entrance/Egress

- operating SPCS (Service and Performance Checkout System)
- operating airlock/hatch
- descending/climbing stairs or operating automatic descent/assent equipment
- loading/unloading supplies
- walking & jumping
- maneuvering
- lifting/placing objects
- stowing/retrieving tools
- using dust cleaning equipment
- cleaning the EMU
- Doning/Doffing outer garments
- Doning/Doffing EMU
- Deploying/using ramps, stairs, or other hand holds or restraints

LRV Use

- Entering/Egressing Rover
- Operating controls (i.e. joysticks, switches, wheels, etc.)
- Configuring LRV attachments
  - mating/demating connectors (e.g. mechanical, electrical)
  - deploying equipment
- Loading supplies, equipment, and consumables
  - module changeout
  - recharging of power supplies
  - emergency backup/equipment

Base Construction/Preparation

- operating construction equipment
- controlling/operating bagging equipment

- configuring construction equipment (e.g. interchange end effectors)
- unpacking and taking inventory of equipment and supplies

Mate Modules

- mating/demating fluid connectors
- mating/demating electrical connectors
- docking/module mechanical coupling

Shielding

- deploying/erecting dust room/porch and quonset hut
- operating automated bagging equipment
- operating teleoperated equipment (i.e. fetch-it robot)
- using hand/foot restraints

Normal Operations

- deploying experiments/sensors
- operating power tools
- operating manual tools
- collecting samples
- accessing/storing tools and equipment
- actuating latches, pins, levers, etc.

Contingency Operations

- using medical kit (i.e. injection)
- using rescue equipment
- using buddy system for shared PLSS supplies (i.e. mate/demate connector for 0_2, fluid, and power)
- performing O-g EVA in cis lunar space during travel to and from the moon
- Manual digging, soil bagging, and emplacement

8.1.2 EVA Workday Length

The global EVA workday length requirement is to achieve the highest levels of productivity by maximizing the amount of work performed in a given time. Pre- and post-EVA operations add an additional 1-1/2 to 2 hours depending upon travel and set-up time. Figure 20 illustrates a sample EVA timeline using this data. Human performance, however, deteriorates if work periods are not limited within physiological boundaries. The results of the trade-off among operational and physiologic and psychological requirements are:

- Nominal workday of 6 hours at EVA worksite (8 hours 26 minutes, including all suit operations and all EVA-related tasks);
- Maximum workday 7 hours and 6 minutes at EVA worksite, and
- Maximum in suit time limited to 8 hours.

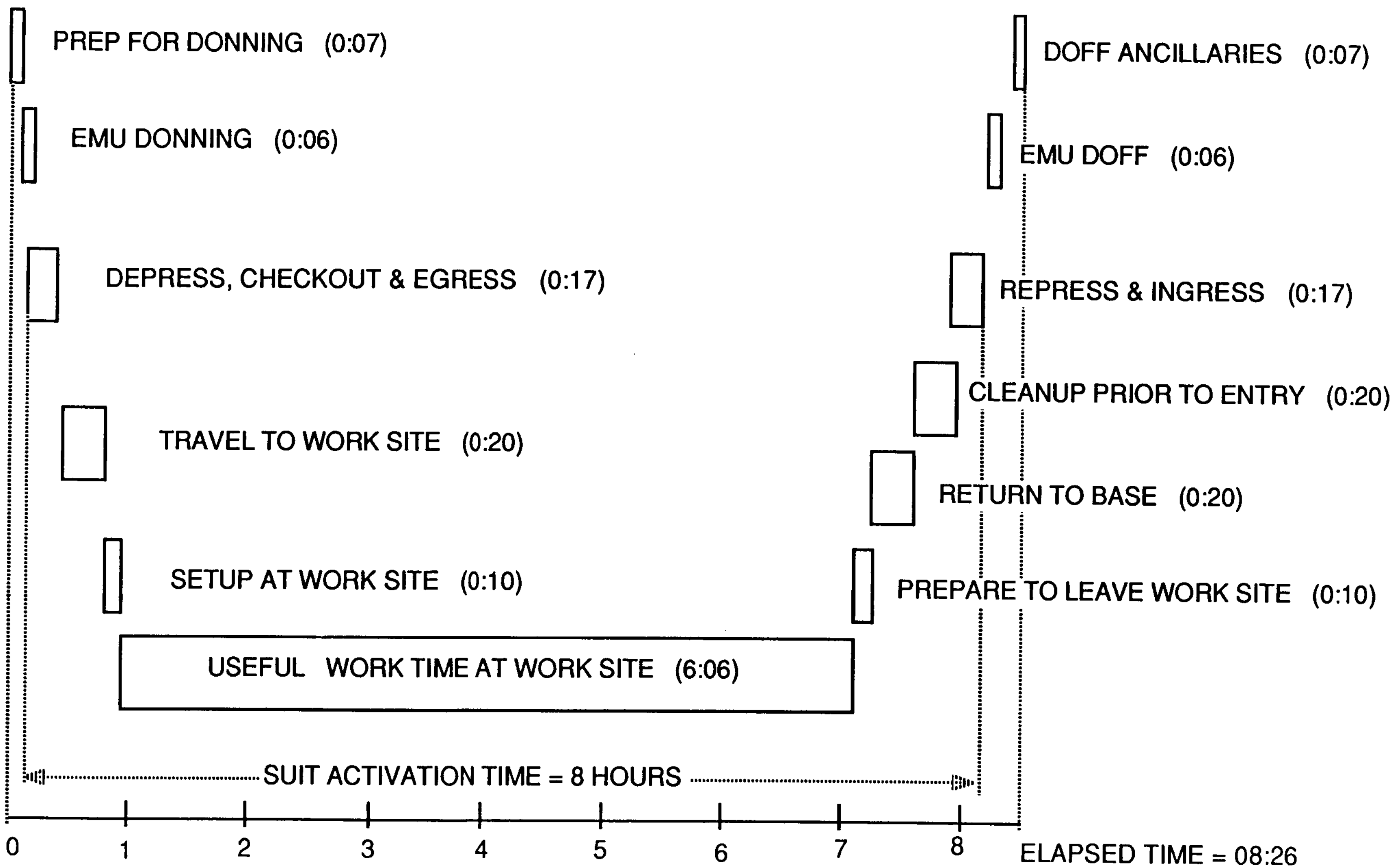


FIGURE 20: SAMPLE LUNAR EVA TIMELINE

8.1.3 EVA Work Period Parameters

The major EVA work period requirements are that the:

- o EVA work periods shall be maximized to ensure maximum productivity within psychological and physiological constraints, and
- o The number of consecutive EVA days per crewmember shall be minimized to preclude excessive boredom.

In the early stages of the mission, the EVA crew will have to expend maximum effort to ensure that a safe haven is constructed as soon as possible. In the study's DRM scenario, this effort could be 3 days of two, 6-8 hour EVA shifts per day. Because the cost of transporting and maintaining a crewmember on the lunar surface will probably be high, the crew productivity should be maintained at the highest possible levels throughout the mission. Unproductive EVA (e.g., ingress, egress, don, doff) due to overhead functions such as dust removal, cleaning, and airlock pressurization, associated with each EVA work period should be minimized.

In the DRM the major task is to build radiation shielding. Because it requires repetitive actions, it is likely to be a boring task. It may, however, be representative of many of the the routine lunar tasks after the base is operational. Therefore, methods of setting up mission schedules or segmenting tasks between missions should be studied.

8.1.4 EVA Duration Optimization

The two major EVA duration optimizations are that:

- o Base resupply (including EVA consumables) shall be accomplished during crew changeout, and
- o Work periods shall be minimized.

The key element of duration optimization is the time the PLSS supplies can last.

Within a given EVA the trade-off must be made between back pack size and mass and resupply of consumables. If the PLSS is worn on the back, the limits on mass of back mounted equipment apply (Section 8.2.3). If not, logistical constraints arise. Therefore, in order to make the job of the hardware easier, limitations on work period arise. These limitations conflict with the requirements on work period parameters.

The operational issues associated with changing out a consumables pack versus a heavier PLSS should be studied. In addition, some operations (e.g. operating a machine, processing and working in a fixed location) may make a stationary PLSS (nonbackmounted) feasible. The percentage of operations which would benefit from this configuration should be assessed and evaluated against the impact on design.

PLSS options which should be assessed from the point of view of operations are:

- o Lighter backpack (venting or non-venting considering launch weight, and the environmental impacts of venting),
- o Suitcase and umbilical,
- o Suitcase with cart (or automated cart),
- o Rechargeable expendibles from LRV
- o Two backpacks
    - 2 to 3 hour backmounted

- suitcase type

- IVA reconfigurable for back or non-backmounted,
- Single backpack with fuel cell or battery changeout.

8.1.5 EVA Translation Considerations

The major EVA Translation Considerations are that:

- LRV's will be provided,
- Simple robotic/teleoperated devices will be provided (Section 8.4.8),
- EVA aids may be required to assist crew translation tasks including:
  - climbing,
  - carrying loads, and
  - traversing rough terrain
- The range of operations will be consistent with a 20 minute working radius (Section 8.3.15) and 8 hours of in-suit time.

Data on limitations of human load carrying ability indicate that many lunar supplies and equipment will exceed the recommended range of operations. For certain operations, the speed of unassisted locomotion will be insufficient for a productive 8 hours in-suit time. Equipment to assist the crew translation will be required as the combination of 1/6-g and wearing a pressure suit inhibits dexterity and mobility.

8.1.6 EVA Rescue Capability

The EVA rescue capability requirements were derived from the following four emergency scenarios: PLSS failure, LRV failure, suit leak, and medical emergency. PLSS failure considered two primary types of suit failure: fan and primary oxygen source. LRV failure considered battery and mechanical faults. Suit leak considered a puncture, or external load which separates the suit at an interface. Medical emergencies considered included accidents such as: crushed bones, cuts due to compound fracture, bruised and broken bones, heart attack, nose bleed, and back strain.

A method of dealing with compound fractures or other situations where in-suit bleeding is possible should be developed. In more complex missions (lunar base evolution) a LRV with a pressurized cab should be studied.

The EVA rescue capability requirements are:

- Systems to allow buddy-shared resources,
- Two LRV's,
- A detachable emergency supply carried on the LRV,
- Two crewmembers shall be capable of transporting the emergency supply and walking back to the habitat,
- PLSS to provide 30 minute O_2 purge flow back-up,
- A rescue device (e.g., rescue sphere) on the LRV,
- The rescue device shall be connectible to the PLSS emergency supply,
- A manipulator shall be provided to assist in lifting injured crew onto LRV (including interchangeable end effectors),

- o An injection patch shall be provided, and
- o An emergency medical kit stowed on the LRV.

8.1.7 Anthropometric Sizing Accommodations

Lunar landing vehicle design (no airlock requirement), and operational constraints would be easier if each crewmember had their own suit. Zero-gravity EVA transfer and contingency operations are also required. Therefore, at least 2 crewmembers must have suits during transit. If each crewmember does not have a suit at the landing site, transportation to base is much more complicated. Therefore, it was assumed that each crewmember will have his/her own suit, and it will be returned to Earth at the end of the mission.

The wide variety of sizes and shapes of people that need to be accommodated implies two major design options:

1) Suits can be custom designed for each person, but the logistics requirements will increase, or

2) Standard suit sizes can be used for all crewmembers. Poor fit severely compromises performance.

Because neither option is attractive, historically a modular approach to suit design has been applied and appears to be the best approach for lunar EVA. If this approach is used, no severe crew size restrictions are anticipated.

Because suits are subject to damage and are critical to mission safety, they should be frequently inspected and overhauled. This process can be more efficiently carried out on Earth rather than on the lunar surface or on a lunar orbiting station (if one is available in the DRM timeframe).

The anthropometric sizing accommodations requirements include:

- o Each crewmember shall have his/her own suit assigned for the entire mission,
- o All suits shall be changed out at the end of each mission, and
- o 50th percentile females to 95th percentile males shall be accommodated.

8.1.8 Logistics

The global requirements for logistics are to minimize time expended on logistics operations, enable work in the dusty lunar environment, and minimize the amount of supply/resupply required. The major requirements by category are:

Storage/Cleaning/Drying/Hygiene:

- o The main suit assembly shall remain in the airlock,
- o The airlock and suit exterior shall be cleaned as required to prevent dust from entering the habitat,
- o The liquid cooling ventilation garment (LCVG) shall be washable/dryable in the habitat laundry facility, and
- o Procedures for suit interior cleaning, decontamination, and drying shall be performed after each EVA and shall require minimum crew time

Servicing/Maintenance and Repair Support Requirements (Spare Parts):

- o The EMU system shall be maintainable by a single crewmember,
- o Maintenance skills shall be those found in the general crewmember population,

- o In order to reduce inventory, the EMU system shall feature component modularity particularly within the following groupings:
    - spare mobility elements (shoulder, ankle, knee, elbow, boots, and waist),
    - pressure regulators,
    - control valves,
    - check valves,
    - electrical components,
    - electronic components,
    - filters,
    - sizing inserts,
    - EVA visors,
    - helmet,
    - LCVG, and
    - gloves.
- o Maintenance shall include sanitary treatment of the EVA elements.

Don/Doff and fit-check/resizing operations:

- o Don/Doff of suit shall be performed through a single opening using a fixture in the airlock,
- o Don/Doff shall be accomplished by a single crewmember without bringing the EMU into the habitat,
- o Standard fit check procedures shall be established at two levels:
    - rough check prior to each EVA by crewmember using suit, and
    - detailed check each month
- o Fit check procedures shall include verification of operation of bearings, and
- o Don/Doff shall require no more than 10 minutes.

A trade-off between endurance life and spares required should be made. For example, 30 EVA days per mission means that the gloves, using current materials such as TMG, will wear out, and need to be replaced.

8.1.9 Maintainability

The major maintainability requirements are that:

- o The EVA system shall be maintainable by a single crewmember,
- o Maintenance skills required shall be those found in the general crewmember population, and
- o Seals and Bearings shall be modular and easily replaceable by a single crewmember.

8.1.10 EVA Hardware Servicing

In order to determine whether a warning is due to a faulty sensor reading or is a malfunction, a built-in checkout ability is required. A major area of future investigations should be the selection of a baseline PLSS design. Once selected, a recharge timeline can be developed.

EVA Hardware servicing requirements are that:

- PLSS trouble shooting shall be automatic,
- A leak detector system shall be provided to isolate leak location,
- Pre- and Post-EVA checkout timelines shall be no more time consuming than those shown in Figure 20, and
- The EMU shall incorporate an autonomous system for sensor checkout.

8.1.11 Cleaning And Drying

The major cleaning and drying requirements are that:

- Suit material shall be cleanable or be protected by outer coverings,
- The EMU shall minimize microbial growth in the suit either by design (materials and configuration) or by maintenance,
- The EMU shall prevent microbial contamination from entering the environment (habitat and lunar), and
- Verification that EMU is sterile and that no microbial contamination is introduced shall be provided.

Other requirements for cleaning and drying are discussed in other categories (e.g., logistics physiological/medical, and dust room/porch).

8.1.12 Caution, Warning, And Checkout

Caution, warning, and checkout requirements were derived from data being developed by Grumman in their SPCS (NAS9-17718) study and include:

- Automated caution/warning indicators shall be provided for all life threatening EMU system hazards (e.g., operational, biomedical, and suit pressure information),
- The EVA system shall provide an emergency locator system either autonomous within the EMU, base/EMU, or a combination (possibly with assistance from ground control),
- The EMU shall provide suit and related system status displays,
- All consumables shall be monitored,
- Displays shall be consistent with physiologic limitations of the crewmembers' ability to receive information (e.g., use of AI to provide information which the crew can use in taking effective remedial action),
- Thermal loop performance shall be monitored, and
- Data collection systems speed shall exceed expected dynamic response of measured parameters.

8.1.13 Communication Requirements During EVA

The communications requirements are dictated by safety and information flow needs. The communications requirements during EVA are:

- o The EMU system shall include the following:
  - nominal, and
  - emergency (automatic crewmember-in-trouble signals).
- o EVA lines of communication shall include:
  - EVA to EVA crew,
  - EVA crew to habitat,
  - EVA crew to Lander/Vehicle,
  - EVA crew to transportation nodes,
  - EVA crew to mission control, and
- o A communications priority system shall be established to regulate communications traffic.

The unique lunar environmental considerations dictate that communications be line-of-sight. Therefore, studies will be needed to determine the impact on the mission infrastructure and operations.

8.1.14 Contamination Prevention/Waste Disposal

The recent Grumman AEVAS study (NAS9-17300) examined the allowable limits of different substances, system leakage, off-gassing limitations, propellant effluents and venting in detail. The contamination requirements developed in the study are valid for the lunar base.

The requirements for waste disposal are:

- o EVA crewmembers shall carry a stowed trash bag, in order to collect litter at the EVA worksite,
- o EVA trash bags shall be disposed outside the pressurized modules, and
- o EVA-generated, in-suit wastes shall be disposed IVA during suit cleaning.

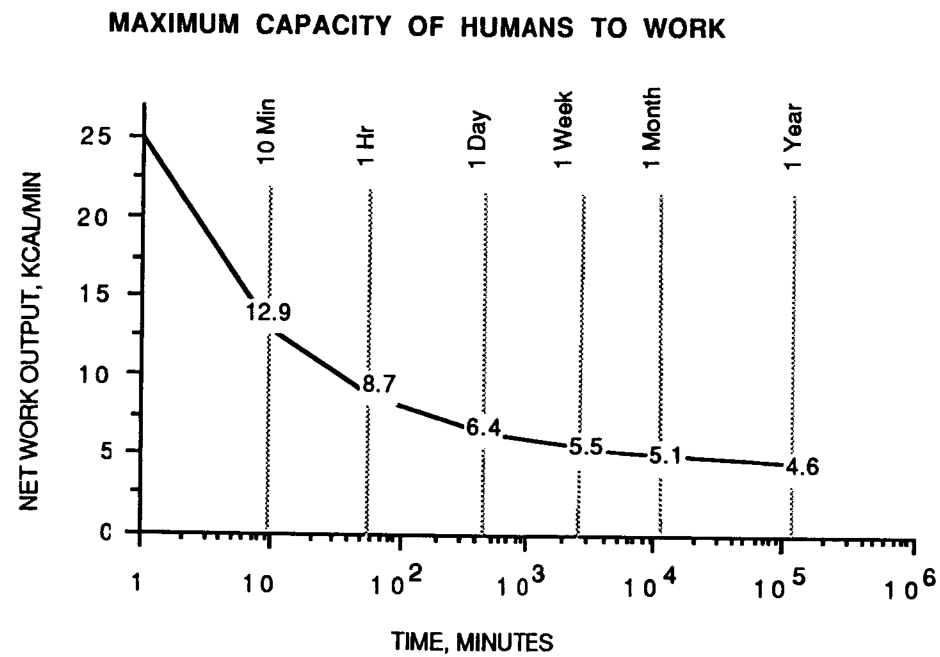
8.2 EVA Man/Machine And Physiological/Medical Requirements

The EVA Man/Machine and Physiological/Medical Requirements are those factors which describe how to sustain crew life and produce equipment with a user interface that promotes productivity. Specifically, when requirements conflict, physiological/medical requirements needed to avoid life-threatening conditions always take precedence.

8.2.1 EVA Duration

No limitations on work capacity were identified for the level of activity required for the DRM (less than 276 kcal/hr, derived from Lehman as shown in Figure 21). Psychological considerations lead, in the absence of physiological constraints, to an optimum work day similar to Earth work durations. In addition, if an in suit snack is the only nutrition provided during EVA, 6-8 hours would be the longest period for normal working conditions between meals. Therefore, 8 hrs, 26 minutes in the suit was selected as the maximum duration.

REVIEW OF DATA OF LEHMAN * SHOWS THAT FOR A SUBJECT PACING HIMSELF TO PRODUCE MAX WORK OUTPUT, HIS OUTPUT RATE BECOMES APPROXIMATELY CONSTANT AS WORK PERIODS BECOME LONGER.



NOTE

1 DAY	=	8 HR
1 WEEK	=	6 WORK DAYS
1 MONTH	=	4 WORK WEEKS
1 YEAR	=	280 WORK DAYS

* REF; PHYSIOLOGY OF WORK CAPACITY & FATIGUE, SIMONSON E. (ED), THOMAS, SPRINGFIELD ILL, 1971

ABOVE DATA FOR NON-CONTINUOUS WORK FOR PERIODS INDICATED, AT MAXIMUM OUTPUTS THAT WOULD NOT PRODUCE EXCESSIVE FATIGUE WHICH LEAD TO PROLONGED RECOVERY TIME.

FIGURE 21: OPTIMUM WORK REST CYCLES

Physiological reactions to high oxygen partial pressures (PO_2) have been observed on Earth and in zero gravity including;

- o decrease in pulmonary vital capacity,
- o decrease in circulating red blood cells (anemia), and
- o central nervous system symptoms in higher concentrations.

It is expected that lunar gravity will not affect O_2 toxicity, therefore, at the present time Space Station PO_2 limits (NASA-STD-3000) should be applied to lunar EVA (See Figure 37 for prebreathe requirements).

PO_2 (psi)	LIMITATION (hrs/period)
10 - 14.7	6 hr / 24 hr period, 18 hr/120 hr period (5 days)
6-10	18 hr/120 hr period (5 days)
3-6	NONE

In order to determine whether this requirement will limit the EVA duration a suit pressure of 8.3 psia was assumed.

With a suit pressure of 8.3 psia and 100% oxygen, the actual oxygen partial pressure is not at 8.3 psia for the entire EVA. Figure 22 shows the partial pressure time history including air-lock pump down and assuming realistic conservative leak rates and concurrent cabin depressuration (see Figure 43, Section 8.4.6). Using the oxygen toxicity limitation from the NASA-STD-3000 the result is a maximum of 2 hours 20 minutes at oxygen partial pressures above 6 psi per 8 hour EVA (Figure 23). This data means that EVA is not limited by this constraint if one EVA is performed each day (5 days of 8 hour missions would yield 11 hours, 40 minutes which is less than 18 hours).

No relevant psychological data exists to determine if 8.5 hours of repetitive tasks in an environment where there are few visual external stimuli will present a difficulty. However, experience indicates that boredom may be an issue. Therefore, approaches to making lunar EVA psychologically acceptable need to be studied.

Therefore the EVA duration requirements are that:

- o The maximum time in the suit shall be 8 hours 26 minutes(for a single EVA),
- o Based on an 8.3 psia suit a maximum of 18 EVA hours per 120 hours shall be at oxygen partial pressures in excess of 6.0 psia (maximum of 3 to 4 EVA days per 5 days), and
- o Crew training, work tasks, and work schedules shall be established to allow an 8 hours and 26 minutes in-suit time for multiple EVA days without incurring psychological stress.

8.2.2 EVA Duty Cycles

Crews have reported that an EVA crew develop methods of working effectively together. Two to three consecutive EVA days was suggested as maximizing productivity, but there is no data to substantiate these requirements other than prior EVA experience. Further operational research and an in-depth literature search should be conducted to verify/modify these assumptions.

The EVA duty cycles are:

- o A minimum of two EVA crew shall engage in EVA activities so that "Buddy" system can be used,

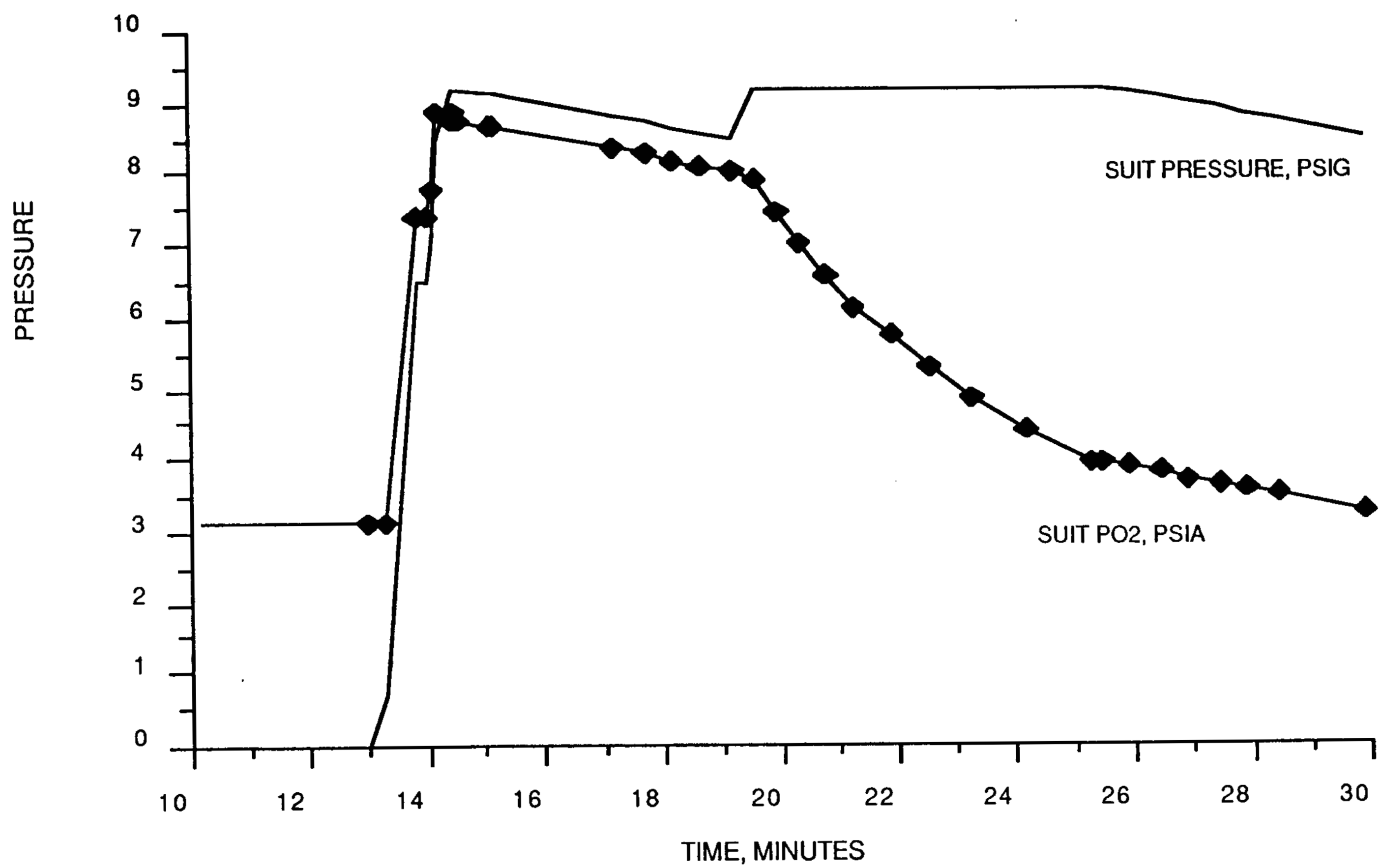


FIGURE 22: SUIT PRESSURE TIME HISTORY

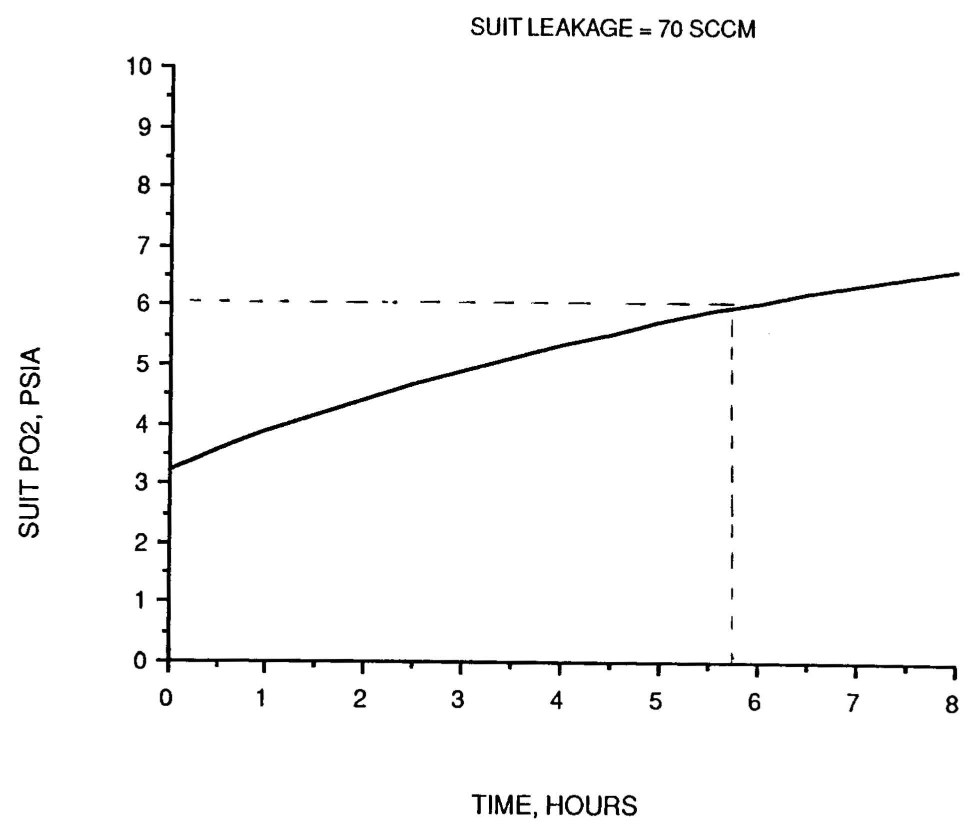


FIGURE 23: SUIT PO2 DURING EVA

- o For a given work cycle (up to 3 days) the same two crew shall maintain the same work schedule,
- o Each 8.5 hour EVA shall contain at least one 30 minute snack break and up to 30 minutes (in a minimum of 15 minute intervals) additional rest,
- o EVA durations of less than 8.5 hours shall have reduced break time depending upon duration,
- o Nominal operation shall be conducted with 1 EVA crew per day which yields a duty cycle for a 4-person mission of 3 days on EVA followed by 3 days off,
- o For emergency operations and initialization of the lunar base, up to two EVA shifts per day shall be performed, and
- o The maximum EVA allowed shall be five days out of every five including up to three two crew shift days consecutively (for a 4- person mission).

8.2.3 Dimensional Limits

It is assumed that the lunar crews will not be required to carry more weight than terrestrial workers on Earth. Therefore limits on tolerance to backmounted equipment indicate that 40 lbs (240 lbs [108.9 kg] in 1/6 g) is an acceptable mass for a 50% percentile male (NBS, 1972 and NASA 1973). The available data on other percentiles and females is sketchy at best. In addition the dimensional limitations are not agreed upon and the data is limited.

Apollo films indicate that normal human gait is not used on the lunar surface. It is unclear as to whether this is due to suit limitations, surface characteristics, or whether this is truly the easiest way to walk in 1/6 g. In order to determine whether suit range of motion and bulk prevents normal walking (1-g style), experiments in suits to determine leg motion in simulated 1/6 g should be undertaken.

Although no high dexterity tasks were identified as part of the DRM, improved glove mobility and dexterity will make all EVA tasks easier and reduce the requirements for specialized tools.

A study of wearing backmounted equipment in a pressure suit should be conducted to determine optimal center of gravity location, load profile, and load magnitude for the 1/6-g environment.

Dimensional requirements include:

- o Suited range of motion shall approach nude range of motion,
- o The suit shall permit "normal" lunar (1/6 g) walking with minimum encumbrance,
- o Backpack (PLSS) mass shall not exceed established standards for back- mounted equipment (average of 40 lbs [18.1 kg] mass),
- o Backpack dimensions will be established based on design considerations including:
    1. Height below helmet
    2. Center of gravity close to the back
    3. Length and depth dictated by hatch and LRV constraints
    4. Environmental constraints
- o Center of gravity shall be located to optimize walking performance without compromising other activities,

- A hand carried PLSS, with umbilical configuration shall be provided for stationary or near stationary tasks (driving, operating heavy equipment, etc.), and
- Configuration change from hand carried to backmounted shall only be performed IVA.

8.2.4 Unique Human Capabilities

The unique human capabilities are primarily related to combining human physical adaptability with human perceptual adaptability. Highly unstructured, complex, dextrous or otherwise unpredictable operations are ideally suited to human capabilities. Robots and other machines cannot currently, nor within the DRM time frame, provide anywhere near human capability. Therefore, the EVA systems should seek to maximize use of these human attributes. Requirements related to unique human capabilities include the following:

- The suit shall provide capability for jumping, loping, climbing, hopping, and bouncing (requiring balance, adaptability and mobility),
- Equipment shall be teleoperated or use supervisory control to maximize use of human perceptual capabilities and minimize the requirement for complex computer control, and
- Data bases on equipment, repair, and other relevant facts shall be available to the crew both in the lunar base and through EMU displays.

8.2.5 Metabolic Profiles

The average metabolic rate during Apollo missions was 234 kcal/hr (936 BTU/hr) Figure 24. The average Apollo crewmember was 69.38 in (176 cm) tall and weighed 163.22 lbs (74 kg). This places the Apollo crew at about the 50th percentile for males Figures 25, 26. The Apollo suits had limited mobility compared to current and developing suit technologies. Although the metabolic rate in the new suits may be the same, the productivity during EVA should be higher because of increased mobility. For the purposes of this analysis, and in the absence of any hard data, approximately 7-10 % reduction in metabolic expenditure was assumed. The average crew size (and therefore metabolic rate) will increase due to including larger males, and will decrease some due to adding females. If the influence of all these factors are approximated an average EVA crewmember will have a metabolic rate of 250 to 275 kcal/hr (993 to 1092 BTU/hr). This calculation is dependent upon the crew mix assumptions and the metabolic data used.

The maximum metabolic rate for 50th percentile female to 95th percentile male (500 kcal/hr [1985 BTU/hr]) was set by the maximum observed (350-450 kcal/hr [1390-1787 BTU]) for strenuous short duration Apollo activities, and the highest walking metabolic rate of 300 kcal/hr (1191 BTU) adjusted for the size factors. Although these rates are not likely to be observed in any crew other than the largest, the suit system must be sized to accommodate this eventuality.

The minimum was set by the estimated stationary metabolic (Figure 27) rate for the smallest female (50th percentile) for the maximum period required for rescue (2 hours). This should also consider the effects of ambient temperature for dark and concentrated sun conditions.

The impact of sizing to accommodate the largest male metabolic rate while still accommodating the smallest female should be analyzed in detail. This requirement should include consideration of system size and weight as well as consumables.

Present Shuttle cooling system including LCVG cannot easily accommodate sharp variations from high to low metabolic rates. Crewmembers often experience sensation of cold in their fingers and toes. Therefore, the cooling/heating approach should be studied to determine the optimal method of regulating body temperature.

	APOLLO 11-17	SKYLAB	STS 61-B	SIMULATION
NUMBER OF SUBJECTS	12	9	2	2
NUMBER OF EVA'S	28	19	2	2
MANHOURS OF EVA	158.74	83.6	12	6
MEAN KCAL/HOUR	234	238	216	250

Formulas used

$$S = 0.007184 * W^{0.425} * H^{0.725}$$

where

S = surface area in m^2

W = weight in kg

H = height in cm

kcal/hr (men) = S * 39.4

kcal/hr (women) = S * 35.9

Sleep = BMR * 0.9 * no. hours

Exercise = BMR * 5 * no. hours

Light work = BMR * 1.5 * no. hours

Medium work = BMR * 2.0 * no. hours

EVA = BMR * 3.5 * no. hours (derived from actual figures for EVA)

Total kcal/day = total of all activities + 5% SDA

FIGURE 24: METABOLIC EXPENDITURE DATA

Source: Lemsco FSSS Study, 1985, NAS9-17430.

Number of crew measured: 72

Average Height (H) = 69.435 (176.365 cm)

Range of 50th percentile H:	68.3 to	70.8 in	(173.48 cm to 179.83 cm)
95th percentile H:	72.8 to	74.8	(184.91 cm to 189.99 cm)
5th percentile H:	63.6 to	66.8	(161.54 cm to 169.67 cm)

No. of Crewmembers approximately 50th percentile:35

<50th percentile:	20
approximately 5th percentile:	5
approximately 95th percentile:	0
between 50th + 95th percentile:	17

FIGURE 25: APOLLO CREW PROFILE DATA

	5th Percentile	50th Percentile	95th Percentile	Source
Height (M)	63.6 in (161.5 cm)	68.3 in (173.5 cm)	72.8 in (184.9 cm)	Woodson
(F)	59.0 in (149.9 cm)	62.9 in (159.8 cm)	67.1 in (170.4 cm)	Woodson
Weight (M)	124 lb (56.2 kg)	168 lb (76.2 kg)	224 lb (101.6 kg)	Woodson
(F)	104 lb (47.2 kg)	139 lb (63.0 kg)	208 lb (94.3 kg)	Woodson
Height (M)	64.4 in (163.6 cm)	68.8 in (174.8 cm)	73.2 in (185.9 cm)	Dreyfus
(F)	59.5 in (151.1 cm)	63.6 in (161.5 cm)	67.7 in (172.0 cm)	Dreyfus
Height (M)	66.8 in (169.7 cm)	70.8 in (179.8 cm)	74.8 in (190.0 cm)	NASA-STD-3000
(F)	58.6 in (148.8 cm)	61.8 in (157.0 cm)	65.0 in (165.1 cm)	NASA-STD-3000

Data from NASA indicates male population is larger than general and women a bit smaller.

Figure 26: HUMAN HEIGHT AND WEIGHT DATA

WT LBS	WT KGS	HT IN HT CM	60 152	61 155	62 157	63 160	64 163	65 165	66 168	67 170	68 173	69 175	70 178
100	45.5		50.0	50.6									
105	47.7		51.0	51.6	52.2	52.8	53.4						
110	50.0		52.0	52.6	53.3	53.9	54.5	55.1	55.7				
115	52.3		53.0	53.7	54.3	54.9	55.6	56.2	56.8	57.4			
120	54.5		54.0	54.6	55.3	55.9	56.6	57.2	57.8	58.5	59.1		
125	56.8		54.9	55.6	56.2	56.9	57.6	58.2	58.9	59.5	60.1	60.8	
125	56.8			55.6	56.2	56.9	57.6	58.2	58.9	59.5	60.1	60.8	61.4
130	59.1					57.9	58.5	59.2	59.8	60.5	61.2	61.8	62.5
135	61.4							60.1	60.8	61.5	62.1	62.8	63.5
140	63.6								61.8	62.4	63.1	63.8	64.5
145	65.9								62.7	63.4	64.1	64.7	65.4
150	68.2									64.3	65.0	65.7	66.4
155	70.5										65.9	66.6	67.3
160	72.7												68.2

BMR (WOMEN) = SURFACE AREA * 35.9

FIGURE 27: BASAL METABOLIC RATE (KCAL/HR) WOMEN AGES 20-50

Source: LEMSCO FSSS, 1985 NASA 9-17430

Therefore, the metabolic requirements are:

- o Heating/Cooling system shall be sized for an average metabolic rate of 260 kcal/hr (1040 BTU/hr),
- o The maximum metabolic rate of 500 kcal/hr (2000 BTU/hr) shall be accommodated for 20 minutes and 400 kcal/hr (1600 BTU/hr) for 1 hour, and
- o A minimum metabolic rate of 50-60 kcal/hr (200-240 BTU/hr) for 2 hours shall be accommodated.

8.2.6 Carbon Dioxide

The acceptable inspired carbon dioxide partial pressures ($PC0_2$) levels are based upon NASA STD 3000 and the Grumman AEVA Design Requirements Study. These levels and durations were deemed to have no adverse medical effects based on current knowledge. However, the value presented in the Grumman AEVA study have not yet been accepted by NASA.

In order to minimize the consumables required to provide $C0_2$ scrubbing, the long-term effects of deviating from these levels must be understood. In addition, there is some evidence that carbon dioxide may be involved in bubble formation during the onset of decompression sickness. Therefore, the interrelationship of the bends and carbon dioxide must be understood to conduct a trade-off between $PC0_2$ and launch weight of consumables.

The carbon dioxide requirements are:

- o $C0_2$ scrubbing shall be provided for maximum metabolic $C0_2$ production as defined by the mission metabolic profiles (average 260 kcal/hr [1040 BTU/hr] gives 367 liters $C0_2$ for an 8 hour EVA),
- o Inspired $PC0_2$ shall be maintained at or below 10 mm Hg (0.19 psia) including:
  - below 7.6 mmHg at metabolic rates lower than 1600 BTU,
  - maintained at 10 mm Hg at 2000 Btu for 10 minutes,
  - maintained at 15 mm Hg at 2500 Btu for 5 minutes,
- o Short term emergency (up to 1 hour) of up to 22.8 mm Hg (0.44 psia) shall be acceptable;
- o During normal EVA $PC0_2$ level must be below 30.51 mm Hg (0.59 psia) (based upon Grumman AEVA study values). If this level is exceeded this will be a decision point for aborting the EVA.
- o $C0_2$ removal system shall prevent levels greater than 22.8 mm Hg.

8.2.7 Thermal Storage Of Body Heat

The accepted thermal storage of body heat (kcal) for comfort is set by the equation:

$$\Delta S = 0.83M(\Delta T_b)$$

where:

$$\Delta S = body \quad thermal \quad storage$$
$$M = the \quad bodymass \quad (kg)$$
$$T_b = \frac{1}{3}T_{skin} + \frac{2}{3}T_{core}$$

Using a core temperature rise of 0.65°C (33.2°F) and assuming the skin temperature remains constant (which is true for systems which provide surface cooling such as the LCVG) for a 70 kg male, the body thermal storage would be 25 kcal (100 BTU). If this change in core temperature is applied to heavier people the allowable storage is greater and for lighter people smaller.

The 35°C (95°F) limit on core body temperature is the temperature below which body temperature regulation capability may be lost (1985 Fundamentals Handbook) therefore an operational limit of 36°C (96.8°F) was selected to be safely above this limit while within the comfort zone.

In the current suit, the method of heat transfer and heat transfer efficiency are affected by the design of the LCVG. The shape of the tubes, the distribution of tubes, the coolant/air pathways, humidity within the suit, the temperature of the coolant, and the time constant of the system all affect the LCVG performance. Data on cooling/heating as it relates to comfort for different ambient conditions should be used in developing a LCVG design.

Cooling control methodologies and data used to set cooling system size assumes that the LCVG inhibits sweating. The effect of sweating on cooling rate has not been studied. If the lunar cooling and comfort requirements are to be met, this relationship must be understood prior to developing a lunar EMU.

Optimization of Cooling/Heating transfer mechanism design will greatly affect the size of the Cooling/Heating system, and the power and other consumables (if any) required to support it. Therefore research into the data available and collection of additional data should be undertaken followed by development of an improved system.

The thermal storage of body heat requirements are:

- o Thermal storage of body heat shall limited to accepted comfort criteria e.g. 25 kcal (100 BTU) for a 70 kg male with 1.8 m^2 of body surface area,
- o Core body temperature shall be maintained at 37°C + 0.65°C (98.6°F + 33.2°F) and at no point even during emergency operations shall it exceed 38°C (100°F) (NIOSH 1986),
- o Heat debt shall be limited to accepted comfort criteria, e.g. 25 kcal (100 BTU) for a 70 kg male with 1.8 m^2 of body surface area,
- o Core body temperature shall not drop below 36.5°C (97.7°F) during nominal operations and at no point below 36°C (96.8°F),
- o Dehydration shall be less than 2% of body weight,
- o Heart rate shall not increase more than 30 beats/minute over resting rate without cooling under nominal conditions, and
- o The distribution of Heating/Cooling should provide efficient cooling and take advantage of known body heat rejection characteristics.

8.2.8 Audio Level, Quality, Range, And Warnings

Normal speech contains components from 100 Hz to 8,000 Hz (Figure 28) but few communications systems require this full range in order to preserve intelligibility. Telephones compress speech using a range from 200 Hz to 3,200 Hz. A trade off between range and other design parameters must be conducted to set the minimum range required. The top end of this range shall be somewhere between 8,000 Hz and 3,200 Hz therefore, the range of 300 Hz to 5,000 Hz was selected for a preliminary requirement.

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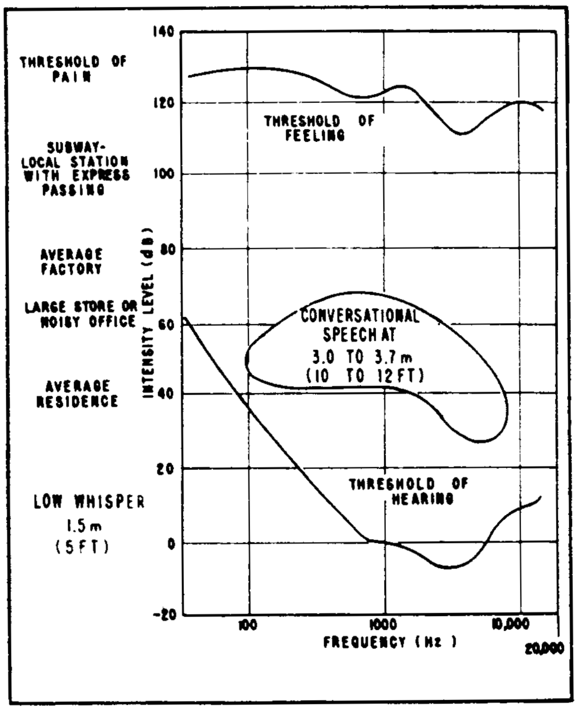

FIGURE 28: HEARING AND FEELING THRESHOLDS FOR SOUND

Source: W.E. Woodson and D.W. Conover, Human Engineering Guide for Equipment Designers. Second Edition. University of California Press, Berkeley and Los Angeles CA 90055. 1964. 490 pp.

Normal speech in a quiet room is exchanged below 50 dBA, whereas in a noisy environment, to retain intelligibility, levels of 75 dBA may be required. Noise levels above 85 dBA begin to have effects on performance and are perceived as unpleasant. It is presumed that the EMU will have some ambient noise associated with it that is transmitted to the crewmember's ear; therefore, the volume range for the communications system was selected as 20-75 dBA. The upper limit was set at 75 dBA to allow a 10 dBA increase in sound level for warnings before reaching the 80 dBA limit.

Audio warnings should be in a range where the human ear is most sensitive (Figures 29 and 30). In some malfunction conditions, it is possible that some static on the communication lines or machine noise could mask the normal tones. Therefore, the tone shall be adjustable in response to this noise or manual override.

Audio level quality, range, and warning requirements are:

- o Voice communication systems shall have a frequency response range of 200Hz to 5000 Hz,
- o Voice communication systems shall have an adjustable audio level from 20 dBA to 75 dBA,
- o Speech level shall exceed the noise level by at least 6 dBA,
- o Audio warning tones shall be modulated to produce a series of beeps,
- o Audio warnings shall be limited to changes in system status which could lead to life threatening conditions,
- o Audio warning tones shall normally be between 500 and 3000 Hz unless ambient noise would mask the signal, and
- o Audio warning tones shall be 10dBA above the voice communications level, but will not exceed 85 dBA.

8.2.9 Visual Displays and Warnings

A great deal of information is required to successfully perform EVA on the lunar surface. The display and warning systems need to be designed to provide that information in a way that is easily understandable and will not interfere with perception of the environment. Current research and development in the area of heads-up displays will yield further information, requirements, and data.

- o Visual displays shall contain the minimum amount of necessary information in order to not saturate perceptual capacity,
- o Warnings shall be visually distinct from all other displays,
- o Heads-up displays shall occupy no more than 16° of the field of view,
- o The smallest angular separation of two objects required to be viewed by the EVA crewmember shall be 1.5 minutes of arc (Figure 31),
- o The smallest angular separation of a target to be discriminated by the EVA crewmember shall be 3 minutes of arc,
- o The smallest interval of time which the EVA crewmember shall be required to view a visual event shall be 100 milliseconds. The minimum viewing time of 100 milliseconds shall be utilized to determine the required background luminance required for the EVA target/worksite region. The maximum temporal frequency that is required for EVA perception shall be $\geq$ 15 Hertz, and
- o Color displays shall be limited to the human color visual field (Figure 32).

ALARM	INTENSITY	FREQUENCY	ATTENTION GETTING ABILITY	NOISE-PENETRATION ABILITY	SPECIAL FEATURES
Diaphone (foghorn)	Very high	Very low	Good	Poor in low frequency noise, good in high-frequency noise.	
Horn	High	Low to high	Good	Good	Can be designed to beam sound directionally, can be rotated to get wide coverage.
Whistle	High	Low to high	Good, if intermittent.	Good, if frequency is properly chosen.	Can be made directional by reflectors.
Siren	High	Low to high	Very good if pitch rises and falls	Very good with rising and falling frequency.	Can be coupled to horn for directional transmission.
Bell	Medium	Medium to high	Good	Good in low-frequency noise.	Can be provided with manual shut-off to insure alarm until action is taken.
Buzzer	Low to medium	Low to medium	Good	Fair, if spectrum is suited to background noise.	Can be Provided with manual shut-off to insure alarm until action is taken.
Chimes and Gong	Low to medium	Low to medium	Fair	Fair, if spectrum is suited to background noise.	
Oscillator	Low to high	Medium to high	Good, if intermittent	Good, if frequency is properly chosen.	Can be presented over intercom system.

FIGURE 29: CHARACTERISTICS AND SPECIAL FEATURES OF VARIOUS ALARMS

Source: H.P. Cott and R.G. Kinkade, Human Engineering Guide to Equipment Design, Revised Edition (Sponsored by Joint Army-Navy-Air Force Steering Committee). American Institutes for Research, Silver Spring MD. 1972. 727 pp. (US Government Printing Office, Wash DC 20402).

CONDITIONS	DESIGN RECOMMENDATIONS
If distance to listener is great	Use high intensities and avoid high frequencies.
If sound must bend around obstacles and pass through partitions	Use low frequencies (<500 Hz).
If background noise is present	Select alarm frequency in region where noise masking is minimal.
To demand attention	Modulate signal to give intermittent "beeps" or frequency to make pitch rise and fall at rate of about 1 - 3 Hz
To acknowledge warning	Provide signal with manual shutoff so that it sounds continuously until action is taken.

FIGURE 30: DESIGN RECOMMENDATIONS FOR AUDITORY ALARM AND WARNING DEVICES

Source: H.P. Cott, ibid.

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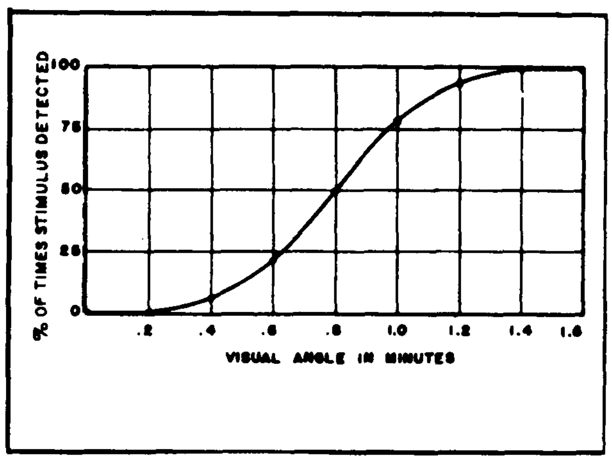

FIGURE 31: RELATIONSHIP BETWEEN VISUAL ANGLE AND THE DETECTION OF STIMULI

Source: C.A. Baker and W.F. Grether, Visual Presentation of Information. WADC-TR-54-160. Aero Medical Lab, Wright-Patterson AFB OH 45433-6573. Aug 54. 115 pp. (DTIC No. AD43064).

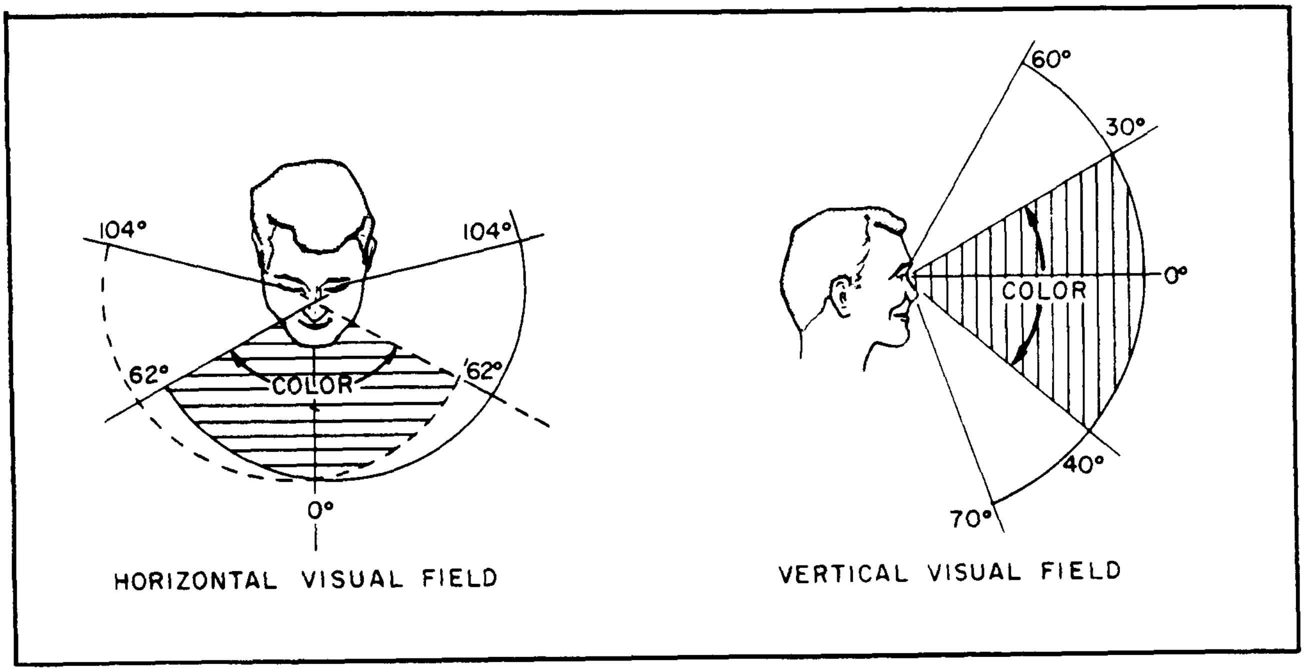

FIGURE 32: THE LIMITS OF HORIZONTAL AND VERTICAL VISUAL FIELDS

Source: Basic Human Factors Considerations for Man-Machine Systems. CVA E9R-12114. Vought Astronautics Division, Chance-Vought Aircraft, Inc., Dallas TX 75221. 15 Jul 59. 160 pp.

8.2.10 Perception Of Surrounding Environment

In addition to the displays, the visor/helmet must interface with the human capability in such a way as to promote perception of ambient events. Human perception capabilities in dark and light conditions are shown in Figures 33 and 34.

- o The visor shall utilize existing helmet and EVA specifications for the optical quality parameters of transmittance/reflectance as found in the EVA operations manual,
- o The visor shall maintain these properties for 3 months,
- o The visor shall be scratch-resistant or have a scratch-resistant protective over-visor in the lunar environment,
- o The visor shall permit viewing in light, dark, or shadowed conditions with normal adaptation.
- o Refractive power tolerance shall be less than $\pm$ .06 diopters due to integration requirements of helmet display system,
- o Direct ambient illumination shall be up to 15,000 ft candles,
- o The EVA crewmember shall have "vision" corrected to 20/20 <u>prior</u> to EVA activities,
- o The total optical power change of the visor/helmet assemblies shall be less than 0.02 $\pm$ .03 diopters, and
- o Critical areas of vision are presented in Figure 35 are required, including:
    - Superior field shall be extended from 90° to 115°.
    - Superior-Temperal field shall be extended from 62° to 80°. and
    - Inferior field shall remain at 70°.

8.2.11 Toxicity

In the closed environment of the EMU, a small amount of toxic substance can rapidly affect crew health. In addition, EMU systems will be brought into the habitat and into transport vehicles where tolerances to toxins is also an issue, as low levels can build up to hazardous levels over the life of the habitat/vehicle. The requirements relative to toxicity are:

- o All non-metallic materials shall meet NASA STD NHB 8060.1B (flammability, odor, outgassing, and combustion products requirements and test procedures for materials in environments that support combustion),
- o Any material in contact with the crewmember shall not produce toxic substances in the presence of urea or other naturally occurring body effluents, and
- o Any material in contact with the crewmember shall not foster the growth of bacteria.

8.2.12 Radiation Tolerance

<u>NON-IONIZING</u>

There is no data that indicates tolerances to Electromagnetic radiation will be different on the lunar surface. For microwaves, OSHA General Industry Standards, Part 1910.97 (Code of Federal Regulation, 1987) state that unlimited exposures below this level are permissible, whereas above this level people may be more prone to develop cataracts. If microwave transmitter locations and strengths are known, minimum safe distances may be established for crewmembers.

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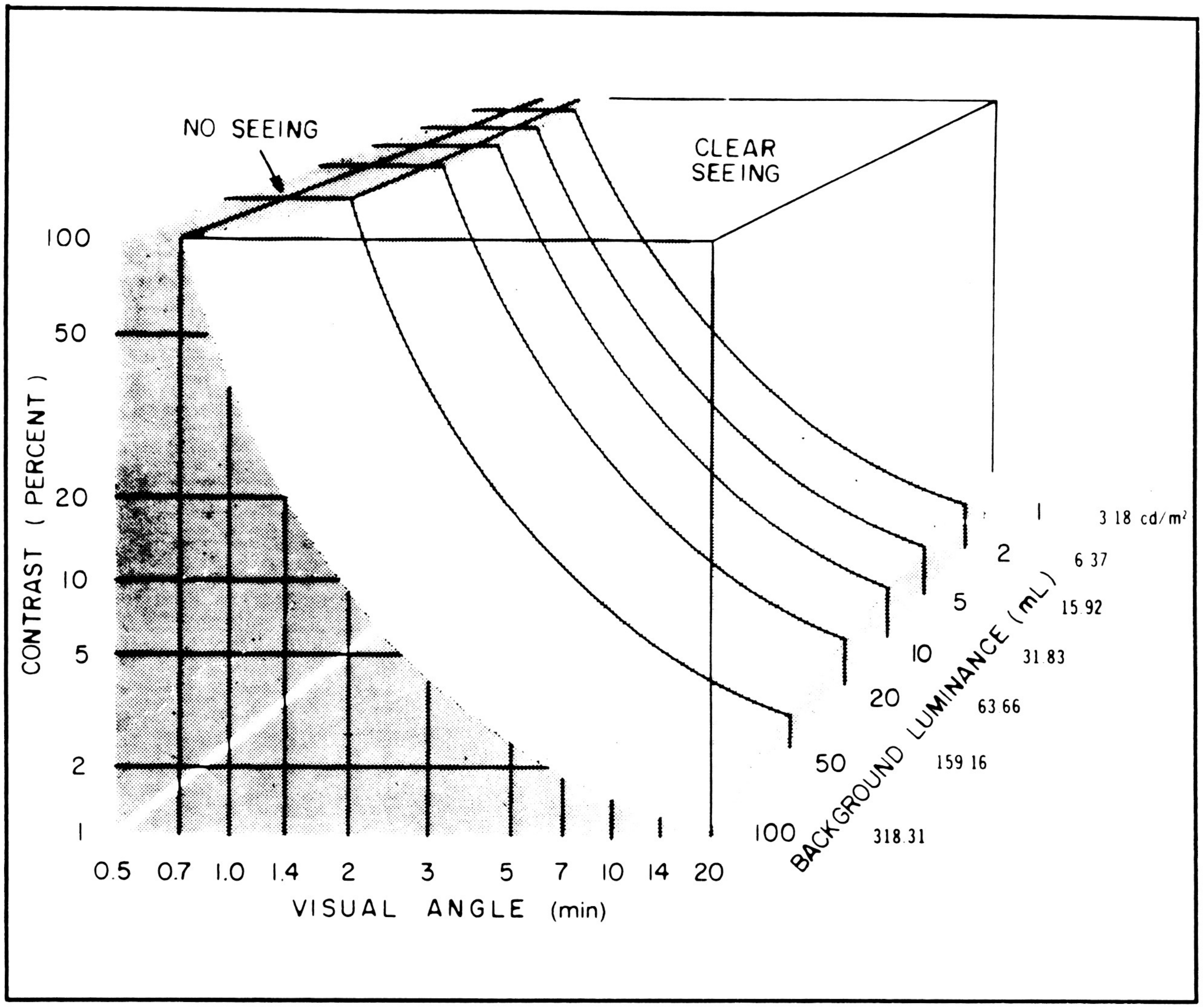
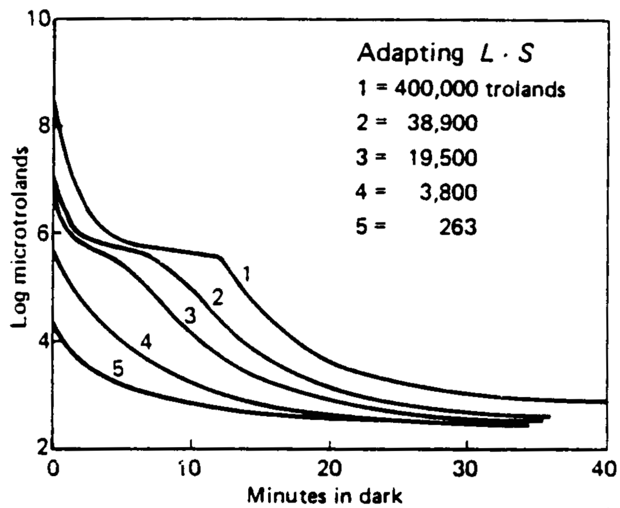
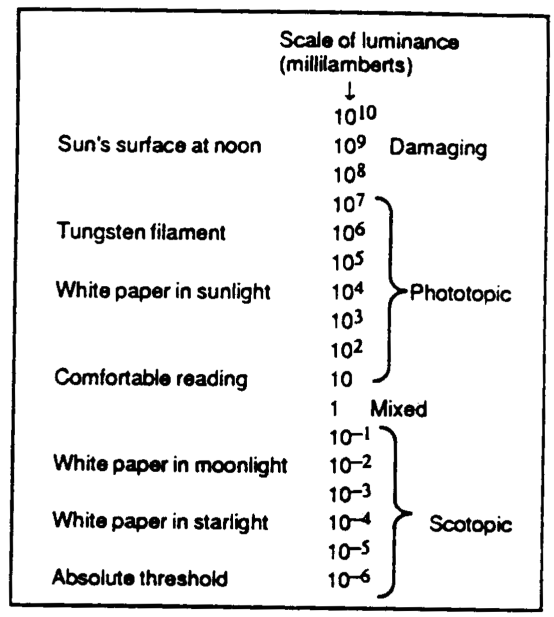


FIGURE 33: VISUAL ACUITY IN RELATION TO CONTRAST AND LUMINESCENCE UNDER DAYLIGHT CONSIDERATIONS

Source: W.E. Woodson and D.W. Conover, Human Engineering Guide for Equipment Designers. Second Editino. University of California Press, Berkeley and Los Angeles CA 90055. 1964. 490 pp.



Dark Adaptation Thresholds



Luminance Values for Typical Visual Stimuli

FIGURE 34: VISION AND ILLUMINATION

Source: NASA-STD-3000.

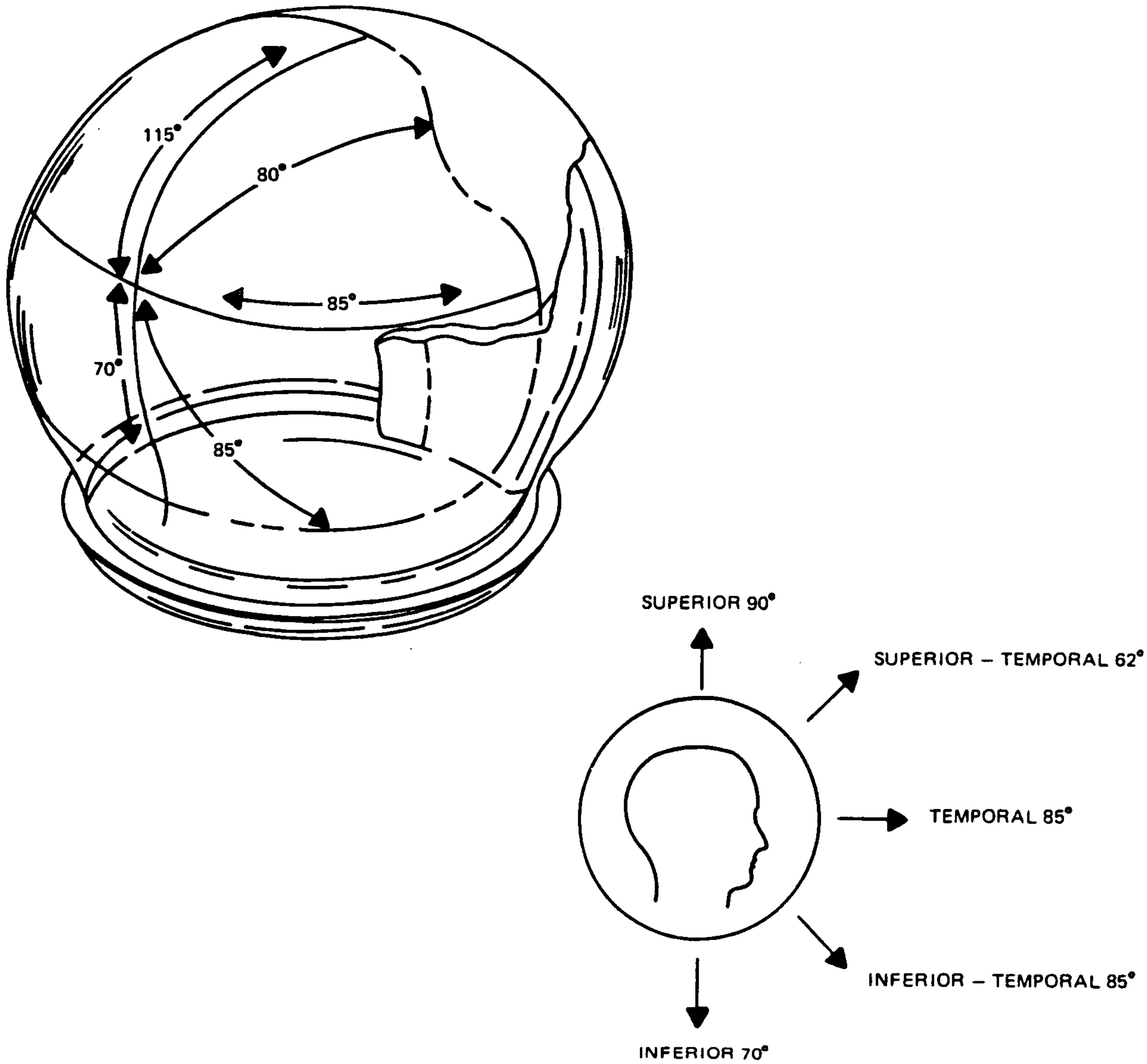


FIGURE 35: CRITICAL FIELDS OF VISION FOR HELMET DESIGN

Source: NASA-STD-3000.

- EM radiation exposure from both ambient lunar and hardware shall be consistent with ANSI and IRPA standards, and
- The EMU systems shall provide warning if microwave densities greater than 10 mw/cm^2 are present.

IONIZING

In order to shield from particle radiation, thick shielding (2-3 meters of lunar regolith) is required. Therefore it is impractical for the EMU to provide radiation protection. The radiation which is most damaging to biological organisms is derived primarily from solar particle events. These occur infrequently (mostly during the middle 5 years of the eleven year solar cycle) and are preceded by the release of X-rays. The X-rays can be detected 20-30 minutes prior to onset of a solar event. Therefore, a suitable storm shelter within 20-30 minutes travel time from all EVA crews in combination with a detection means (X-ray detector) either on the lunar surface or in a satellite will protect EVA crews from this radiation.

- EMU mass per unit area will be less than 20 gm/cm^2 to avoid generation of secondary neutrons from cosmic radiation, and
- Ionizing radiation exposure limits shall not exceed the National Council on Radiation Protection Committee 75 (1986) proposed limits.

8.2.13 Personnel Hygiene

The importance of personnel hygiene increases when a crew must spend a large percentage of mission time inside a closed environment. In the current EVA suit configuration, air is circulated throughout the suit interior and coolant is circulated through tubes in contact with the skin. The air may pick up debris (e.g., velcro dust, dead skin, and bacteria) during its pathway (prior to filtration) and some of these materials could be inhaled. Therefore all hygiene steps performed prior to EVA which serve to limit this possibility should be performed.

In addition, the lunar missions will range from one to three months and the suits must be used repeatedly during this period. In order to safely allow repeated use, the cooling garment (if any, or other EVA undergarment) must be cleaned and kept free of bacteria or other substances (mold, mildew) build-up. Minimizing the amount of human-originating contaminants that are introduced into the EVA system will make this task easier. Post-EVA cooling garment cleaning/disinfecting will accomplish the remainder of the required cleaning.

Development of an EVA cooling garment (or undergarment) which can be easily and rapidly washed in automated equipment is necessary to make the cleaning requirement tractable over extended missions. In addition, the garment should be fabricated from materials which do not themselves promote bacterial growth.

Pre-EVA hygiene requirements are:

- Skin shall be cleaned to remove cosmetics, ointments, dead skin, and bacteria,
- Urinary, fecal, and menses collection devices shall be attached/applied as necessary,
- Grooming functions shall be performed (i.e. shaving, hair grooming, nail trimming, etc.), and
- Urination and defecation shall be performed as necessary.

Post-EVA hygiene requirements are:

- Disposal of urine, feces, vomit, and menses shall be performed as necessary,
- Shower and other body cleansing shall be performed as necessary, and

- Cooling garment (if any) and suit interior shall be cleaned/disinfected as necessary.

8.2.14 Waste Management/Containment

There are various factors which can influence the amount of urine excreted during a given period. A daily urine volume between 600 and 1,600 ml is considered "normal," with 1.2-1.7 L/day common. Temperature can effect urine production greatly. In one U.S. Army study, the urine production rate was 40 ml/hr before exposure to cold and 100 ml/hr after 4 hours of cold exposure. Exposure to increased temperature (+15°C) can cause a decrease in urine volume of 200-500 ml/day in the absence of cooling. The amount of urine produced in 0-g for one person per day has been reported between 1,330 ml and 1,630 ml and 740 ml in an 8 hour period. A single micturition can contain up to 800 ml and be delivered at 50 ml/sec. Therefore, a 1,000 ml collection device should suffice.

The normal feces bolus varies in size from 100 to 200 mm long by 15 to 40 mm in diameter and weighs 100 to 200 grams. Without a feces collection device normal feces would probably not escape from the cooling garment (or undergarment). But if a crewmember had digestive tract problems (diarrhea), the water content of the feces, normally about 54% water by weight, could contain 2 to 3 times the normal water content. If excreted into the suit, it could present a major safety hazard. Therefore, a feces collection system sized for 700 ml has been selected.

The maximum volume of expelled vomitus can be 1 liter of solids and fluids. The average vomitus volume is more likely to be 200 to 500 ml. Inhalation of small amounts of vomit (20-40 ml) can cause serious physiologic reactions. Vomitus adhering to the visor can restrict vision and vomitus entering the LSS may render the LSS non-functional. As vomiting is a reflex action, there is often little warning before onset, and there is often little capability for control of head position. Therefore an easy to use, effective, and small (when stowed) vomit containment system is warranted and a 750 ml size was selected.

There is little data describing the relationship between size, gender, work rate, and urine produced. It seems reasonable that a small woman would not require the same capacity collection device as a large man. Since comfort, in some designs, will be related to device capacity or size, this issue should be studied. The relationship between sweat and urine production in the presence of cooling also needs to be studied to accurately determine device capacity.

The primary environment of use of this EVA system is 1/6 g where the waste products such as vomitus and feces would tend to settle within the suit; and therefore, in the unlikely event where they were produced, they would not present a serious hazard. However, a need for these suits to be used for contingency 0-g operations have been identified, where these problems are applicable.

In long-duration missions such as those associated with lunar base, absence from EVA duty due to minor illness, such as colds, would be less likely and, therefore, these systems would be desirable.

The design of the containment systems may benefit from utilizing the 1/6 g present on the lunar surface. Therefore a 0-g contingency system and a separate nominal lunar operations system may be required. The waste management/containment requirements are:

- In-suit urine collection (both male and female) shall be provided to accommodate 1,000 ml of fluid,
- In-suit feces collection shall be provided to accommodate 700 ml of feces (liquid and solid),
- In-suit vomitus collection shall be provided to accommodate 750 ml of vomit,
- Collection devices shall cause the user a minimum of discomfort,
- Removal of used collection devices shall be simple and shall not allow spillage, and

- o Collection devices shall contain wastes and prevent contamination/fouling of other suit systems (e.g. air supply and visor surface, among others).

8.2.15 Food-Water

Dehydration has been linked to the development of decompression sickness (Look, 1951, Warwick, 1942, and Draguzia, 1978) and should be avoided at all costs. A water supply should be easily accessible and its use encouraged. An accepted guideline for most activities is that 1 ml of liquid be injested for every 1 kcal (3.97 Btu) of energy expenditure. If it is assumed that the average energy expenditure over a 6-hour EVA will be 250 kcal/hr (1000 BTU/hr), then 1.5 liters of water would be required to prevent dehydration. The accepted rule of 1 ml/kcal (0.252 ml/Btu) stated above is for normal working conditions, not with use of an LCVG. The relationship between work rate, cooling supplied, sweat rate (if any) and urine produced should be examined.

The daily caloric requirements for 0-g IVA and EVA crews were studied by Lockheed (Figure 36). The study concluded that the differences between EVA and IVA crew requirements ranged between 317 and 550 kcal/day (259 and 2184 Btu/day), on EVA days depending upon size and gender. Although these data are not directly relevant to 1/6 g, it is generally accepted the the metabolic cost of 0-g EVA is at least as high if not higher than 1/6 g and, therefore, can serve as a useful upper limit.

Although a lunch break may seem desirable in order to provide more "Earthlike" food in a conventional format, there are several operational reasons why this type of break may not be feasible for lunar EVA. With a zero prebreathe suit, the amount of time required to initiate EVA activity has been greatly reduced. At a minimum, the time required to pressurize/depressurize the airlock will be added to the overhead if a lunch break is used. With the Space Station pressures this would add approximately 1 hour. In addition, it would be necessary to add the time required to travel from the work site to the habitat and back which could be as much as 40 minutes total. Therefore between 1 hour and 1 hour and 40 minutes would be added to each EVA. This amount of time seems to be an unwarranted detraction from productive work. If the longest EVA were 6 to 7 hours of useful work, then it would not be unreasonable to assume that only a snack or drink would be consumed during this time as often people eat dinner 6 to 7 hours after lunch with little refreshment in between.

In order to deliver 750 kcal (2978 Btu) of nutrition easily within the suit, in a palatable form, and with minimum residue alternatives to the current fruit bar (200 kcal [794 Btu] each) such as low residue liquid nutrients should be considered as well as alternative dispensing methods.

Food-Water requirements are that:

- o Drinking water shall be provided with, the amount depending upon crew (size, weight, sex), EVA duration, and crew preference,
- o The in-suit water dispenser shall be sized to accommodate 1.5 liters of water and shall be easy to use,
- o Food shall be provided according to crew (size, weight, sex), EVA duration, and crew preference,
- o The in-suit food dispenser shall accommodate up to 750 kcal of food, and
- o Foods shall be palatable and dispensing shall be simple and not interfere with other suit functions.

8.2.16 Medical Care/Facilities

Decompression sickness or air embolism can occur when crewmembers are exposed to low barometric pressures or when the pressure drops rapidly. It is important to begin treatment as soon as possible. The impact of between 20 minutes and 2 hours delay on the onset of treatment, particularly

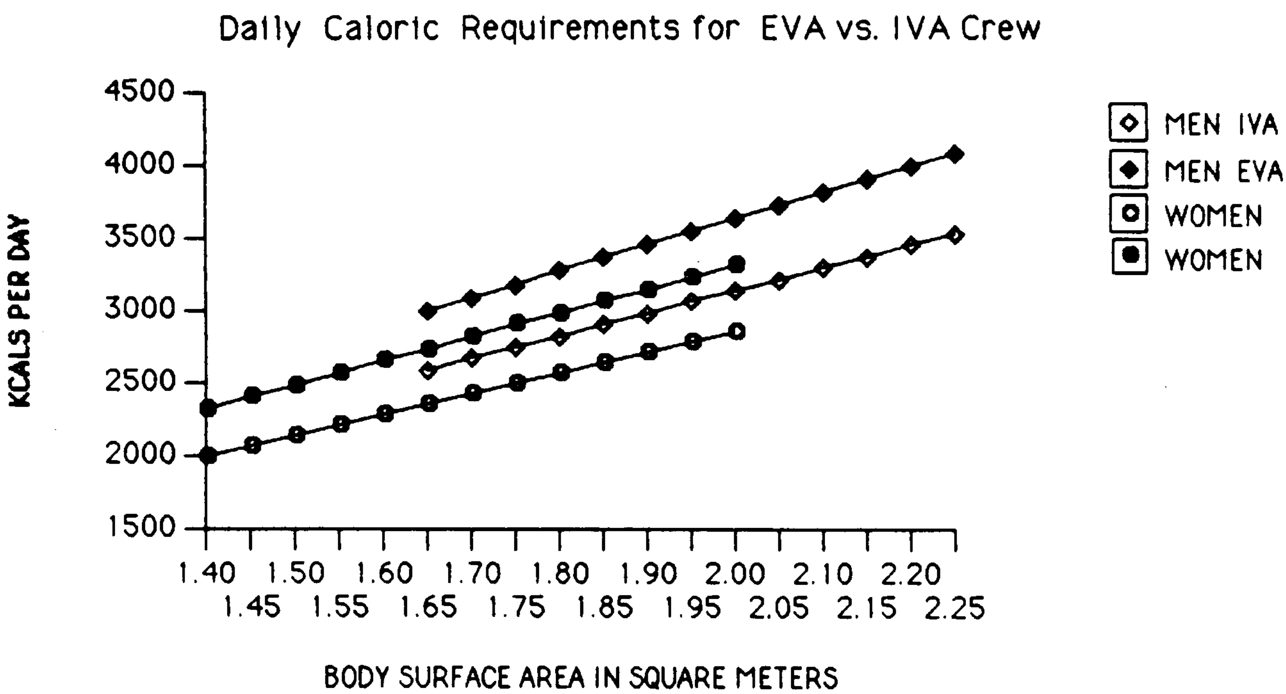


FIGURE 36: NUTRITIONAL REQUIREMENTS

Source: NASA Monthly Report, MA-67, Lockheed EMSCO Contract NAS9-17430.

hyperbaric, should be evaluated. It is possible that a crewmember may be at the edge of the work radius (distance from the habitat) when an accident occurs. If the crew can walk or ride back, then it is likely that they would have no more than a 20 minute delay until treatment. If two crew are incapacitated simultaneously, it is estimated it may take up to 2 hours to effect a rescue. Therefore a limited portable hyperbaric treatment capability (such as the personnel rescue sphere discussed in NASA Tech Briefs, Fall 1983), may be desirable. The need for such a system and the system attributes should be studied.

Despite the best design efforts, some conditions may arise where the EMU becomes a site for undetected bacterial or other contaminant growth. If these conditions occur, skin abnormalities may be the first indication of a problem. Therefore treatment for these types of afflictions shall be provided.

In some situations, improper cleaning, or bearing, or seal failure may allow some lunar dust to enter the EMU or the habitat. If the air filtration system does not totally remove particles, they could end up in the eye of the crewmember, therefore an eyewash capability shall be provided (e.g. eye cup with pressurized water rinse).

When performing construction or other forms of physical labor, either without automation or with automated or semi-automated equipment, some incidence of muscular injuries, and bruises, or pinch injuries will be observed. If lunar EVA becomes a routine operation, medical care for these injuries shall also be provided. A study of other life-threatening EVA injuries should be undertaken to determine the components of a medical kit carried to remote work sites either on the LRV's or by the crew. In addition, the feasibility and location of a suit injection patch, as well as alternatives should be investigated. The medical/care facilities requirements are:

- A hyperbaric treatment chamber shall be provided,
- The chamber shall be large enough to accommodate two EVA crewmembers,
- The hyperbaric chamber shall provide all facilities necessary for care of disbarism sickness for up to 38 hours including:
  - 100% oxygen supplied by mask,
  - ECG, BP, and HR measurements,
  - IV therapy,
  - injection,
  - drinking fluids,
  - urine collection, and
  - chamber pressure capability of at least 6.0 times normal operating pressure,
- Facilities shall be provided for care of the following potential EVA related medical conditions: skin irritations/abrasions, skin infections/conditions, pinch injuries, eye irritations (such as from lunar dust), back strains/sprains and other muscular injuries, and
- A medical injection patch or suitable alternative shall be provided on the EMU.

8.2.17 Atmosphere Composition/Pressure

There are many factors which influence the choice of suit and cabin pressure. The choice is essentially a compromise between biomedical and technical factors which include: permissible oxygen partial pressure, choice of dilutent gases (if any), allowable total pressure, long-term effects of altered atmospheric composition, size and weight of hardware, fire hazard, safety during cabin

decompression, time to prepare to EVA, thermal environment for equipment cooling, and EVA glove dexterity and suit mobility. From a habitat launch weight and suit mobility and dexterity point of view the lowest possible habitat and suit pressure would be desirable. If the safety constraint that the oxygen concentration not exceed 30% by volume is added, the minimum safe total pressure is about 8 psia. At this habitat pressure, the suit pressure could be about 4 psia (Figure 37). However, this pressure would require prebreathing for about 4 hours which would not be desirable. At this low cabin pressure, equipment would require forced air cooling. Without other physiologic driving factors the trade-off then becomes size and weight versus commonality with other systems. If Space Station is used as a staging point, then two options are possible: one option uses the same pressures, and the other uses the time between leaving Space Station and arriving at the habitat airlock to readjust the pressures. The first option has many advantages from a simplicity point of view and from evaluating potential contingency operations. If launch is direct from Earth, or from some yet to be identified location (such as cis lunar space), the same arguments remain in favor of the Earth-normal 14.7 psia atmosphere.

Atmosphere composition requirements are:

- o Habitat pressure shall be 14.7 psia,
- o Habitat PO_2 shall be 3.04 psia, and
- o Habitat nitrogen partial pressure shall be 11.44 psia.

8.2.18 Suit Pressure

Once the trade-off between suit and habit pressures is conducted, the suit pressure can then be selected based on the previously mentioned criteria. The requirements are:

- o Suit pressure shall be 8.3 psia. This can change if cabin pressure during transit to and from the moon is lowered from atmospheric pressure. In this case preconditioning of crewmember will be required.
- o Suit shall be 100% breathing O_2.

8.2.19 Biomedical Data-Monitoring And Management

In order to insure crew safety during EVA, the status of crew vital signs must be monitored. These measurements need to be sufficiently refined to indicate only whether or not the crewmember is in need of assistance or rescue. For this purpose one parameter might suffice. During the early stages of long-duration lunar occupation, collection of more detailed biomedical data would be desirable to better understand the limits of human performance in 1/6 g. In addition some of these parameters may be useful for automated control of the crew cooling/heating system. The primary biomed data collection and monitoring system could be a small, self-contained system worn by the crew which includes storage of normal values and provides caution and warning. The unit could be small and subsequent to EVA could be plugged into the main data collection unit at the habitat for downloading the data. Thus constant telemetry of data would not be required. In this case telemetry would only be initiated if a problem arose.

The biomedical data-monitoring and management requirements are:

- o Provide for monitoring and telemetering of the following vital signs:
  - heart rate,
  - respiration rate,
  - metabolic rate,
- o Provide a minimum of four additional channels for additional biomedical parameters for research, or health monitoring during illness or stress,

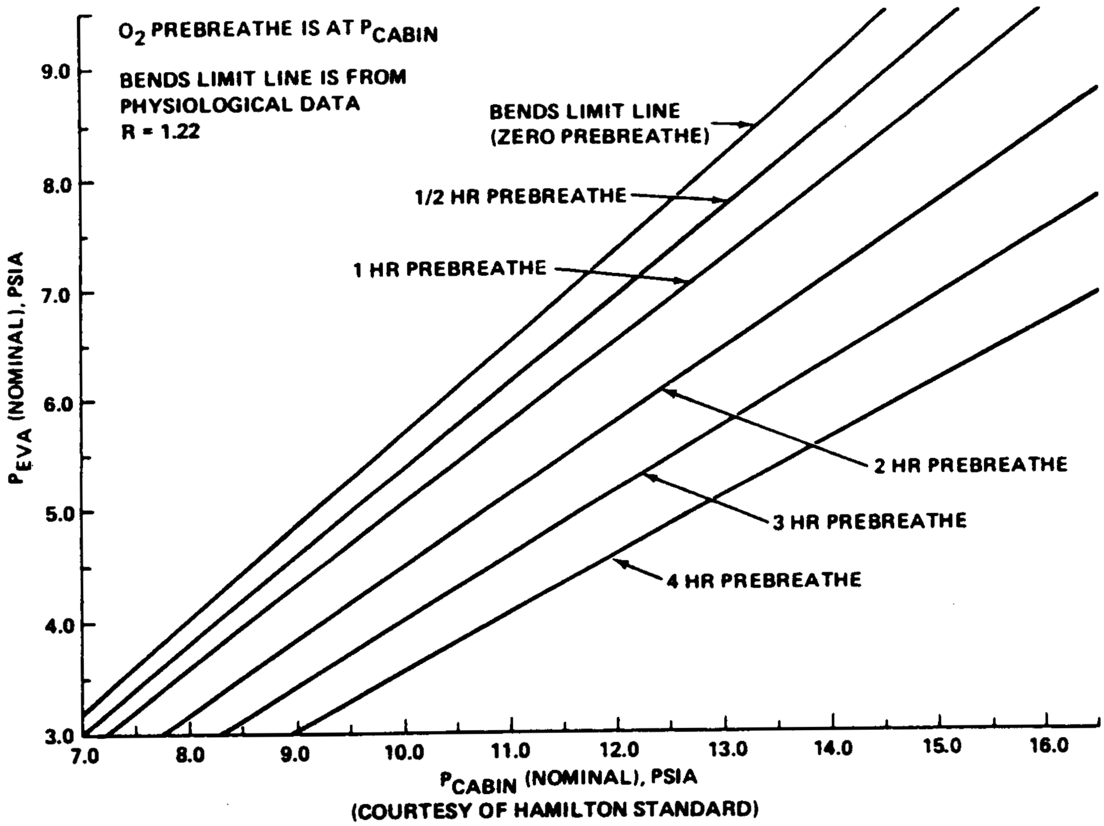


FIGURE 37: PREBREATHE REQUIREMENTS

Source: Grumman AEVA Study 1985,NAS9-17300.

- o Provide for measurement of cumulative and instantaneous radiation dosage,
- o Store for each crewmember normal values for all measured parameters,
- o Provide caution/warning for all measured parameters at hazard level,
- o Provide a habitat based automated data collection system, and
- o All biomedical equipment shall be easy to use, non-invasive, and reliable.

8.2.20 Medical Care

Medical care for long-term lunar operations is a significant area of investigation. Those aspects of medical care specific to the mission AEVA have been covered in 8.2.16.

8.3 EVA Hardware Requirements

Once the aspects of the lunar environment which could affect an EVA crewmember were characterized, and the human physiological requirements to sustain life were identified, a description of the hardware systems characteristics was made. This requirements list is intended to provide the hardware designer and crew alike with a preliminary understanding of the important aspects of EMU system design for lunar EVA.

8.3.1 Design Loads, Operating Life, And Safety Factors

It is anticipated that the crew will require space suit assemblies for 0-g contingency operations, and possibly vehicle transfer (booster/station to lander). In addition the lander will be greatly simplified by all crew being EVA-capable (no airlock required). All other requirements were derived from space experience and from Space Station plans. In order to apply these to the lunar environment, various trade studies should be performed.

Among them are a cost/benefit analysis of 10 year life versus shorter life. In addition, externally-induced loads, impacts, and abrasions are environmentally dependent and, therefore, need to be studied as no data specific to setting these requirements have been identified.

The design loads, operating life, and safety factors requirements are:

- o Lunar space suit assemblies shall be returned to Earth for refurbishment after every mission,
- o Operational life of the elements that return to Earth with the crew shall be equivalent to Space Station suit life (936 hours of EVA use).
- o The elements that remain on the lunar surface shall be able to support EVA for a period of 10 years with maintenance,
- o In accordance with Space Station practice, all parts of the EVA system shall have a useful life of 10 years with maintenance,
- o In accordance with current practice, design life shall be based on 4 times the projected average actual use (Grumman AEVA Study, P.331), and
- o In accordance with anticipated Space Station practice, sufficient redundancy shall be incorporated so that no single point failure will compromise mission success, and no dual failure will be life threatening.

8.3.2 EVA Tools

The tools required should be as analogous to an Earth based home shop as possible to maximize the potential to deal with unplanned repair and other contingency requirements. Small items and tools,

if dropped, may get lost in the lunar surface dust; and, therefore, systems to prevent this loss from happening should be provided. In conjunction with more in-depth mission and operational analyses, the requirements for and details of tools should be examined.

The EVA tools requirements are:

- o The EMU system shall provide standard and easy-to-use tools which include:
  - suit compatible handles,
  - a portable tool box,
  - Earth-analogous equipment,
  - a tool holder,
  - a portable cleaner,
  - small item retention device, and
  - current EVA tools (listed in EVA PLBD Contingency Tools Description Document, 1981).
- o Tools shall be designed to be able to be tethered, and
- o Dust could get into EVA tools, (e.g., sockets or ratchets for power tools); therefore, they shall be easily cleanable.

8.3.3 Restraints/Workstations

Much of the servicing and maintenance on the large equipment will take place on or near the tool shed; therefore, it requires compatible facilities. Similarly, the IVA workstation will fill the needs of EMU.

The restraints/work stations requirements are:

- o Crew restraints (See Section 8.3.11),
- o LRVs shall have seat-belt-type restraints,
  - o A tool shed shall be provided with a workstation including:
    - a work bench,
    - lights,
    - tool restraints,
    - power,
    - a dust removal system,
    - equipment storage, and
  - o A dedicated IVA workstation shall be provided for EMU cleaning, servicing, maintenance, and checkout.

8.3.4 Communications

There are two communication system types: suit-integral and "Snoopy." The "Snoopy" system adds an additional don/doff step, therefore, the suit-integral system is recommended. The EMU

subsystems will produce their own noise which could interfere with communications. As this noise can be characterized for all conditions, it can be electronically eliminated. Other communications requirements are discussed in Section 8.4.1.

- o Communications systems shall be integral to the helmet, and
- o Noise from the EMU systems shall be filtered out.

8.3.5 Crewmember Translation

Lunar soil has a varying particle size and density and thus could range from powdery to rocky. Thus abrasion characterics of boot soles in various terrain conditions should be established. The design of boot soles to obtain required traction for EVA tasks can then be developed.

- o see LRV's (Section 8.4.7), and
- o EMU bootsoles shall provide sufficient traction for all projected conditions, including dusty rock surfaces.

8.3.6 Propulsion System Assessment

No requirements for an MMU style system were identified, surface propulsion will be accomplished through LRV's and on foot, and therefore issues associated with propulsion technology are not relevant. A study of the impact of landing sites near the habitat should be made to assess the minimum walking and rover speeds required for safety from solar flare events (20 minute radius from shelter).

- o no requirements for alternate propulsion were identified, and
- o EVA crew shall remain in habitat or quonset hut during launch/landing

8.3.7 External Configuration

Operational constraints dictate that the external configuration of the suit should minimize the logistics requirements and should be simple to use, maintain, and clean. Long-duration exposure to O-g has been shown to cause many physiologic changes, including postural ones. It is presumed that 1/6 g may cause some long-term changes, therefore suit adjustability and modularity will be important. These features are particularly important during the DRM because the long-duration data bases on human physiology will not yet be available. In addition to accommodating changes, a method for assessing glove fit, dexterity, tactility and fatigue should be developed to determine whether the size adjustments are adequate. These parameters will not be identical to 0-g, but may rely heavily on that data. The preliminary external configuration requirements are:

- o The EMU system shall minimize spares and logistics through use of commonality where possible,
- o The EMU design shall permit resizing on the moon,
- o The EMU shall accommodate long-duration mission body changes,
- o The EMU shall be anthropomorphic and accommodate a 50th percentile American female to a 95th percentile American male with respect to:
  - suit segment sizes,
  - volumes,
  - suit mass, and
  - backpack mass,

- o EMU joints shall satisfy operational requirements (dexterity, mobility, resistance), and
- o EMU gloves shall be custom fitted and allow dexterity and tactility.

8.3.8 Thermal Environments

To estimate the radiative heat load expected for a cremember while working in a crater on the lunar surface, over and above the direct solar insolation, diffuse black-body type radiation from the lunar surface is assumed. This assumption is expected to give good estimates given that;

- o Specular reflections are not expected over most of the lunar terrain.
- o Surface emissivities are near unity due to the re-entrant surface characteristics.

The radiation from solar insolation is the radiative flux, 0.14 Watt/cm² times the projected area of the crewmember attenuated by the suit emmisivity. The radiation from the lunar surface to the crewmember is given by the equation;

$$Q = \sigma T_s^4 \varepsilon_{LS} \varepsilon_S A_L F_{L-A}$$

where the constants are defined as;

Stephan -Bolztman Const - σ
Surface Temperature - T_s
Crater Surface Area - A_L

Lunar surface emmisivity - ε_{LS}

Suit emmisivity - ε_S

Shape Factor - F_{L-A}

The shape factor, F_{L-A} is the fraction of energy leaving the lunar surface which impinges on the suit. The factor can be found by using the reciprocity theorem which allows F_{L-A} to be written as;

$$F_{L-A} = \frac{A_L}{A_A} F_{A-L}$$

where F_{A-L} is the fraction of diffuse radiation leaving the crewmember surface area A_A, which would impinge on the lunar surface, and can be approximated by the ratio of solid angle subtended by the lunar surface to 4 π steradians (a full circle);

$$F_{A-L} = \frac{1}{2}\left[1 + \frac{H-Z}{\left[H^2 + \frac{D^2}{4}\right]^{\frac{1}{2}}}\right]$$

where H, Z and D define the crater/crewmember geometry, shown in Figure 38. The radiative load from the lunar surface onto the space suit can then be written as;

$$Q_R = \sigma T_s^4 \varepsilon_{LS} \varepsilon_S A_A \frac{1}{2}\left[1 + \frac{1 - \frac{Z}{H}}{\left[1 + [\frac{D}{2H}]^2\right]^{\frac{1}{2}}}\right] = q_r A_A$$

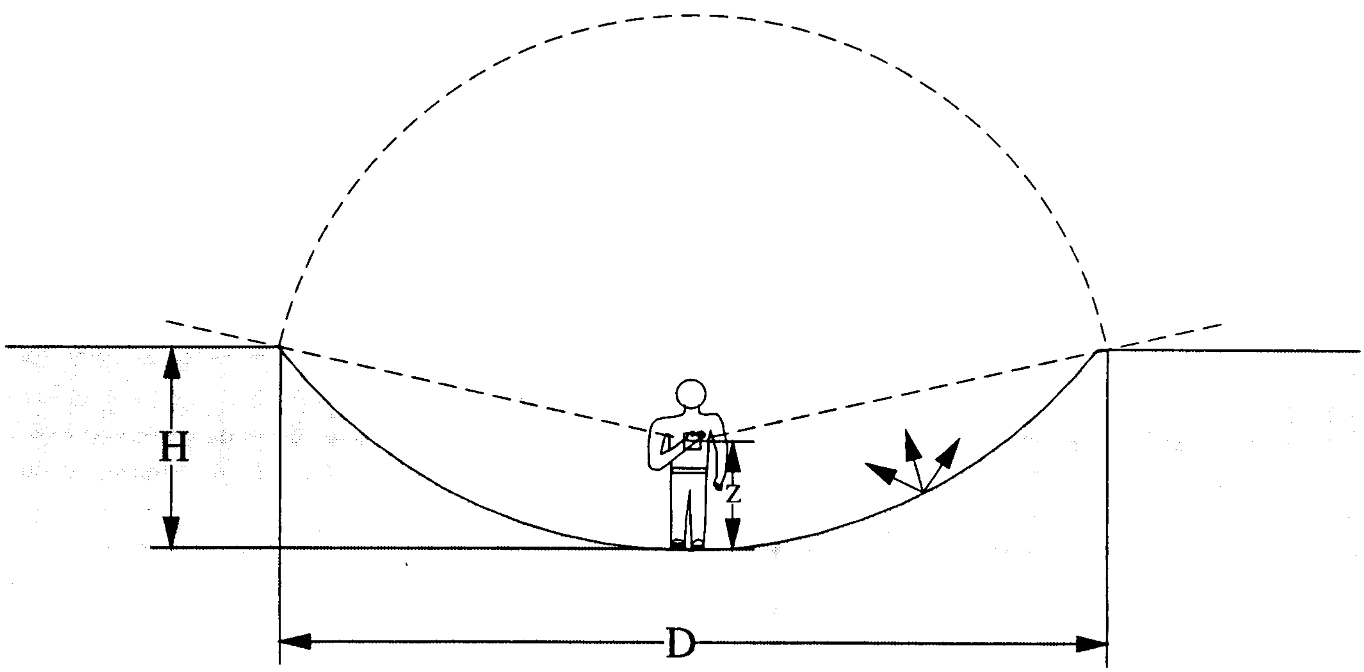


FIGURE 38: CRATER/EVA CREWMEMBER GEOMETRY

For the conditions; surface temperature, T_s = 150° C, surface emmisivity = 1, helmet emissivity = 0.5, suit emmisivity = 0.787, and crater aspect ratios, Z/H=0.5, D/2H=2.75, projected suit area to solar insolation 500 cm^2 and the estimated suit surface area 18,000 cm^2, gives 35 Watts (120 BTU/HR) direct solar load and 1500 Watts (5100 BTU/HR) from the lunar surface, for a total radiation heat load of 1535 Watts (5,260 BTU/HR). An effective concentration factor is therfore approximately 44, owing primarily to the difference in projected surface areas and emissivities.

The actual heat load that must be dealt with by the cooling system will be the sum of the total radiative heat load and the heat generated by the crewmember minus the heat re-radiated from the suit. A typical value of heat generated by a male crewmember for normal activity levels is 1.65 Watts (5.56 BTU/HR).

The heat re-radiated from the suit depends on the conductance and emissivity of the suit material, the air temperature within the suit, and the convection coefficient on the inside of the suit. A heat balance demonstrates the dependency:

$$Q_{re-rad}/A_A = RAD\, q_{re-rad} = \varepsilon\sigma T_1^4 = q_r - q_c$$

Where q_c is the heat penetrating through the suit due to conduction, radiation, and convection on the inside surface;

$$q_c = \frac{1}{R}(T_1 - Tair)$$

Where R is the thermal restance along the path:

$$R = \frac{1}{h} + \frac{1}{C}$$

h is the convection coefficient on the inside of the suit, and is assumed to result from natural convection. A typical value will be taken as h = 1.13 x 10^{-3} Watts/CM^2 °C (2 BTU/HR ft^2 °F)

C is the suit conductance, which reflects the conductivity and emissivity properties of the layers comprising the suit material:

$$C = \frac{k}{x} + \frac{\sigma}{m}\left(\frac{2}{\varepsilon} - 1\right)\frac{T_1^4 - T_2^4}{T_1 - T_2}$$

where:

k : thermal conductivity

x : thickness

T_1 : absolute temperature of outside suit temp (°K)

T_2 : absolute temperature of inside air temp (°K)

m : number of spaces between radiation shields

ε : emittance of radiation shield surface

Using typical material properties, allows the conductance to be written in terms of the temperatures:

$$c = 2.81x10^{-14}\left[\frac{T_1^4 - T_2^4}{T_1 - T_2}\right] + 1.873x10^{-7}\frac{Watts}{CM^{2\circ}K}$$

Solving for the above non-linear equations gives the re-radiated heat flux.

$$Q_{re-rad} = 1506Watts\left(5143\frac{BTU}{HR}\right)$$

Finally, the heat load on the cooling system can be calculated

$$Q_{load} = 1540Watts - 1506Watts + 2Watts$$

$$= 38Watts\left(129\frac{Btu}{HR}\right)$$

The thermal environmental requirements are:

- o The suit materials shall provide protection from the harsh lunar thermal environment (-170°C to +150°C),
- o The suit shall provide thermal protection from hot or cold surfaces normally encountered,
- o The suit shall be designed to allow detection of temperature changes prior to suit or person damage (especially the glove) by incorporating sensors in critical locations,
- o Suit accessories shall be available for contacting abnormally hot or cold surfaces, and
- o The effects of solar concentration in craters can yield a maximum to 36 Watts (122 BTUs) additional heat load on the crewmember and shall be accommodated.

8.3.9 EVA Rescue Requirements

As mentioned the EMU systems include provision for crew-in-trouble signals transmitted to various locations. One of these locations is the habitat/base. If such a signal is received, the time for a rescue crew to arrive at the site ranges from 30 to 50 minutes depending upon the site location and speed of crew reaction (see Figure 20 for pre-EVA timeline). It is possible that this time delay is inadequate. In such cases the remote call capability of the LRV's, fetch-it robot, and other equipment (e.g., construction) may provide a more rapid return capability.

8.3.10 EVA Operational Life

Each suit will see approximately 30 EVA days per mission or 255 EVA hours. In addition a contingency 0-g EVA should be factored in. If the safety factor is set, then the operational life can be determined. A safety factor of 1.5 yield strength and 2 ultimate strength should be used to be consistent with Space Station. In the absence of more precise data these limits were set to be consistent with Space Station.

- o Design loads, Operating Life and Safety Factors, (See Section 8.3.1) and
- o Operational Life of Tools, LRV's, and other EVA systems shall be 10 years with maintenance.

8.3.11 EVA Worksite

In 1/6-g a fall from a height greater than 2m could cause serious injury, thus restraints should be provided. The operations where this fall is possible are those involving working in, on, or around the base modules, quonset hut, or shielding.

- o Crewmembers shall use safety tethers and handrails when climbing structures more than 2m high,

- The EMU system shall provide the following types of illumination:
  - area lights (non-EMU),
  - portable/adjustable, and
  - helmet/suit mounted,
- Tools shall be provided including:
  - hand (Section 8.3.2), and
  - power tools,
- Handheld cameras shall be provided at the worksite including:
  - video, and
  - still.

8.3.12 Sharp Corner/Impact Requirements

In order to establish some preliminary requirements a variety of data was used which was not lunar-derived but was a worst-case for other systems. Therefore, these data should be analyzed further. In addition, test procedures should be established, testing should be conducted, and potential abrasion with lunar soil should be studied.

Loads and cutting edge requirements were derived from ESA SLP/2104. Penetrometer requirements were derived from tests conducted by Hamilton Standard/ILC Dover (ref. Contract NAS9-15150), but the radius was modified as per the ESA/NASA document.

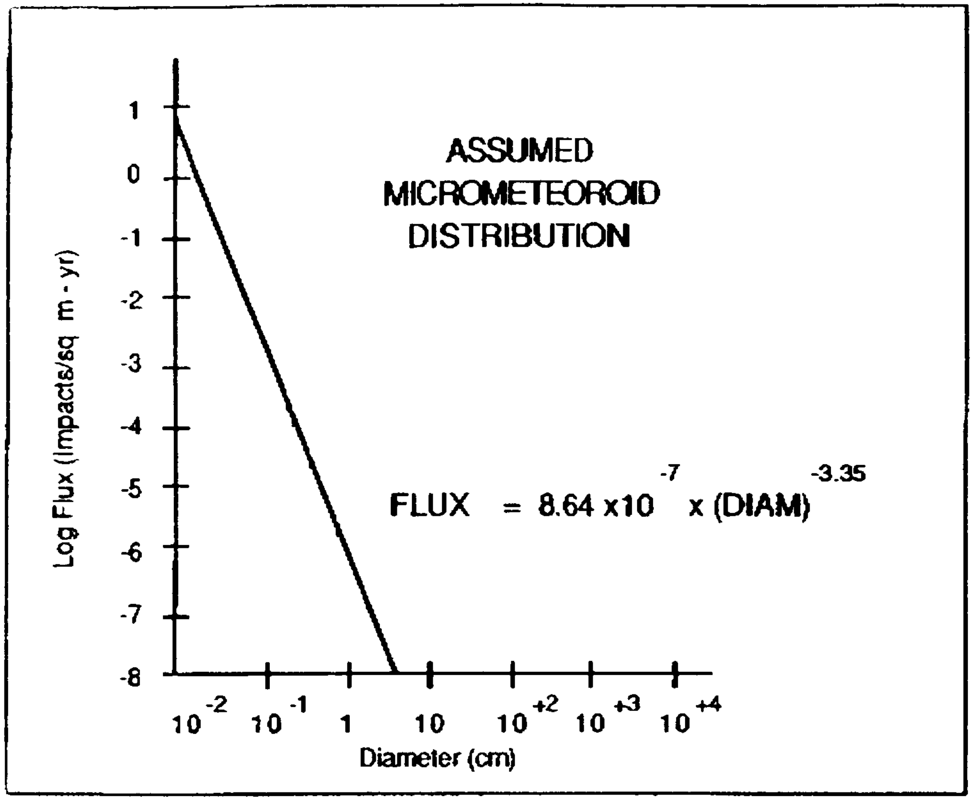
Consideration must be given to potential hazards and how they may be encountered. In and around the habitat/vehicle during movement for crew transfer or emergency EVA, the crew may grasp objects, levers, turn wheels, or sustain inadvertant collisions with or kicks to equipment edges or corners. On the lunar surface, the crew will come into contact with lunar soil and rocks, construction equipment, dust removal equipment and other tool surfaces which may have sharp edges (e.g. shovel blades). Therefore, the requirements are:

- All external elements of the EVA system while, at normal operating pressure, shall not sustain any leakage or permanent damage after being subjected to the following:
  - Penetration: A force of 187 lbs. (85 kg) applied by a penetrometer consisting of a 4 in (10 cm) regular tetrahedron with a 0.01 radius 3-D corner
  - Cut: A mass of 20 lbm (9 kg) applied to a 0.01 in (0.025 cm) radius edge and the edge drawn across the component at a velocity of 5m/sec for 4 in (10 cm)
  - Impact EVA-suited crewmen can cause 13.4 ft-lb (1.85 kg-m) worst case load at max velocity of 5ft/sec (1.52 m/sec) or steady state load of 124 lbs (56.2 kg) and

8.3.13 Micrometeoroid/Space Debris

Analysis of the current EMU (Figures 39, 40) on the lunar surface, using an assumed distribution (which needs to be validated for lunar surface conditions) shows the following:

- Cumulative no-penetration probability for 1,000 hour exposure is 0.9933, and



ASSUMED CHARACTERISTICS		
avg velocity,	v	20 Km/sec
avg density	r	0.5 g/cu cm

STEPS IN ANALYSIS:

1. MINIMUM PENETRATION ENERGY IS EXPERIMENTALLY OBTAINED, AND PARTICLE DIAMETER IS CALCULATED
2. DISTRIBUTION CURVE GIVES FLUX
3. PROBABILITY OF PENETRATION = FLUX x AREA x TIME x SHIELDING
4. PROBABILITY OF NON-PENETRATION = 1 - PROB OF PENETRATION

FIGURE 39: ANALYSIS OF MICROMETEROROID PENETRATION

HOLE SIZE THAT LEAKS 1.2 LB OXYGEN IN 30 MIN.

SUIT PRESSURE	HOLE DIAMETER
8.2 psia	0.17 cm
6.0 psia	0.20 cm

TOTAL AREA OF EMU = 2.86 square meters

IMPACTS/SQ M/YR FOR 0.17 PARTICLE = 3.27E-04

PROBABILITY OF NO HIT IN 1000 HR WITH SHIELDING FACTOR OF .5

$$= 1 - \frac{3.27 \ X \ 10^{-4} \ X \ 2.86 \ X \ 1000 \ X \ 0.5}{8760}$$

$$= 0.99995$$

FIGURE 40: ANALYSIS OF LEAKAGE DUE TO MICROMETEOROID PENETRATION

Arthur D. Little, Inc.

- o Probability of no hit with a micrometeoroid that would exhaust the SOP in 30 minutes is 0.99995.

Further analyses are required to characterize the expected environment and to quantify the lunar EMU reliability requirements. These shall include the probability of sustaining no micrometeoroid penetration of the EMU, and the probability that the largest resultant hole will not exceed the SOP capacity in 30 minutes.

8.3.14 Sand/Dust And Surface Terrain Conditions

In Section 7.0 a detailed description of the lunar geotechnical considerations is given. From this description, the specific requirements related to sand/dust (lunar soil) and terrain are:

- o Dust penetration into bearings shall be minimized,
- o Bearing design shall consider the possible requirement for changeout due to dust penetration,
- o Thermal control surface design shall consider dust and shall be cleaned/regenerated,
- o Optical surfaces shall be cleaned in a manner so as not to cause abraison,
- o Spread footings shall be provided for settlent sensitive structures,
- o Mining of regolith shall be limited to slopes and depths consistent with local soil properties,
- o The habitat site shall be chosen based upon local load bearing capabilities, and
- o LRV's shall traverse paths consistant with acceptable terrain slopes.

8.3.15 Radiation Environment

The environmental and physiological considerations lead to the conclusion that the primary radiation threat to the crew is from solar flares. A suit that could protect a crewmember from this threat would be so massive that it would be totally impractical. A shielded vehicle is also impractical. Therefore, the crew must be warned of impending flare (20-30 minutes between X-rays and flare), and must be able to get from any EVA location to a shielded habitat or shelter. Thus the remaining radiation concerns are addressed in the following requirements:

- o The visor shall protect the eyes and face from UV radiation,
- o The suit mass per unit area shall be low enough to avoid generation of secondary neutrons from cosmic radiation (<20 gm/cm^2, Shuttle suit is 0.2-1.2 g/m^2), and
- o A solar flare detecton and crew warning system shall be provided (using X-ray detection).

8.4 <u>EVA Hardware Interface Accommodations Requirements</u>

An EVA crewmember comes into contact with a wide variety of other (non-EVA) systems while performing, preparing for, or cleaning up after an EVA. This contact takes the form of physical interactions (touching or using equipment) or data (sending or receiving). This creates requirements for systems which would not exist if EVA were not necessary and places some additional requirements on some systems which also interact with IVA crews. Operationally EVA places requirements on logistics, maintenance, resupply and spares by adding to or modifying requirements associated with other (non-EVA) systems. The following section examines these issues.

8.4.1 Communications

Preliminary communications requirements have been derived in part from the Advanced EVA System Design Requirements Study, December 1985. The requirement for the ability to control LRV's remotely was developed to reduce the number of LRV's required and provide an additional margin of safety.

Communications network link requirements are as follows:

- o The nominal operations with two crew EVA at a given time are:
  - EVA1 crew to EVA2 crew (RF),
  - EVA crew to IVA crew,
  - EVA crew in airlock to EVA crew outside of habitat,
  - EVA crew to crew in lander,
  - EVA crew to crew on LRV,
  - EVA crew to crew in shelters,
  - EVA crew to Space Station,
  - EVA crew to Earth, and
  - Earth to EVA crew.
- o Some emergency, contingency, or advanced missions may require 4 EVA crewmember at a given time, thus the following communications shall be provided:
- EVAS to EVAS (Conference),
- EVAS to space station (Conference),
- EVAS to Earth, and
- Earth to EVAS.
- o Preliminary communications implementation

TWO EVA CREW

- EVA1 to EVA2 (RF),

RF communications

Duplex voice

- EVA1, EVA2 to habitat crew,

Duplex voice

- EVA1, EVA2 to relay(s) to Earth,

Duplex voice

- Earth uplink via relay(s) to EVA1, EVA2,

Duplex voice

- EVA1 & EVA2 to EVA3 & EVA4, and

Duplex voice

- EVA1, EVA2 to back-up rescue.

Simplex voice

IVA CREW IN HABITAT

- EVA1, EVA2 to IVA crew,

Duplex voice

Auto relay to Earth

- Earth uplink via relay(s) to EVA, and

Duplex voice

- Color TV camera (various locations) to habitat, to space station and to ground.

FOUR EVA CREW, MAX

- EVA1, 2, 3, 4 to space station,

Duplex voice, auto space station/relay(s) to Earth

- Earth uplink via relay(s) to EVA 1, 2, 3, 4,

Duplex voice

- EVA1, 2, 3, 4 to back-up rescue, and

simplex voice, auto space station/relay(s) to Earth.

- Color TV camera (various locations) to habitat, to space station and to ground.

o Navigation aid and position indication requirements are:

- All LRV's shall be controllable by crew in the habitat or while EVA,
- EVA LRV control shall be available via the helmet mounted display and voice commands or manual controls, and
- EMU's, LRV's, and all construction equipment shall incorporate locator devices.

8.4.2 Logistics

Preliminary logistics weight/volume requirements have also been derived from the Advanced EVA System Design Requirements Study.

o The resupply period shall be the same as the mission period,

o Components in the lunar EVA support equipment (e.g., LRV's and tools) that shall be replaceable on the lunar surface include the following categories:

  - Scheduled maintenance items,
  - Regenerable components to support quick-turnaround for contingency EVA's,
  - Low-MTBF items, and
  - Select damage-prone items,

- Spares shall be provided to replace expendables for the mission/resupply interval duration, and
- Preliminary estimates of weight and volume logistics requirements for a crew of four and a mission/resupply interval of 90 days are as follows:

EMU SPARES -One time delivery; replenish as required

ITEM	QUANTITY	WT (lbs [kg])	VOL (ft^3 [m^3])
EMU PLSS	2	834 (378.3)	13.5 (0.382)
Additional PLSS LRU's	9	312 (141.5)	6.1 (0.173)
EMU ORU's	5	18 (8.165)	4.0 (0.113)
SSA Sizing elements sets	4 sets	92 (41.77)	26 (0.736)

EMU & SERVICE EQUIPMENT RESUPPLY 90 DAYS - Size sensitive, damage prone and limited life items

ITEM	QUANTITY	WT (lbs [kg])	VOL (ft^3 [m^3])
PLSS Components	25	1000 (453.6)	10.4 (0.295)
Gloves	10 pairs	40 (18.14)	2.6 (0.074)
Ancillaries	25	250 (113.4)	25 (0.708)
LCVG (Dry)	4	25 (11.34)	3 (0.085)
Service Equip Filters	Set	0.6	0.2

EMU SERVICE EQUIPMENT SPARES - One time delivery; replenish as required

ITEM	QUANTITY	WT (lbs [kg)	VOL (ft^3[m^3])
Pump/Separator	1	10 (4.54)	0.2 (0.006)
Power Supply/Batt Chge	1	50 (22.68)	0.5 (0.014)
Fan	2	20 (9.07)	.4 (0.011)
Solenoid Valves	2	1 (0.45)	0.01 (0.0003)
Compressor Head	1	10 (4.54)	0.05 (0.001)
Communications Equip	2	1.0 (0.45)	0.04 (0.001)
Pneumatic Ancillaries	5	10 (4.54)	.5 (0.0142)

8.4.3 Safe Haven And Portable Shelter

In this study all DRM operations are accomplished within the 20 minute radius necessary to ensure safety from solar flares. For this scenario shelters are not necessary. If operations were desired beyond this range, shelters or additional habitats would be required to protect from flare events. Portable shelters cannot provide sufficient radiation protection. Therefore, if this type of scenario was desired several approaches to providing shelter could be envisioned. They include:

- Multiple habitats with shielding,
- Radiation shielding shelters (unpressurized),

- a shelter can consist of a low-man supporting structure covered with regolith-filled bags,
- access is provided via a curved tunnel for radiation protection,
- crew can stay in shelter suited for 2 to 4 days,
- emergency supplies and a small pressurixed module for emergency use can be carried on LRV (LRV can be driven into the shelter),

o Radiation shielding shelters (pressurized),

- outpost type minimum capacity module at multiple locations.

In a phased approach to building up the lunar base infrastructure, the quickest way to increase crew range is with small unpressured enclosure. If a network of these were set up with emergency supplies in each, the crew would then be able to safely construct, emplace and shield other pressurized modules and habitats.

8.4.4 EVA Crewmember Autonomy

In order to maximize autonomy from the main lunar base, the EVA crewmember requires certain types of information while conducting EVA including:

o Mission operations procedures,

o EMU diagnostic information,

o EMU consumables status, and

o Control and display capability for robotic external equipment.

Safety is an important consideration for EVA autonomy. This requires that safety-related measurements must be available to all the crew, whether IVA or EVA, and that out-of-tolerance warnings be communicated to all. Safety-related measurements include locator devices which shall be part of the EMU.

The most effective method of providing information to the EVA crew is a helmet-mounted display, which shall be incorporated in the EMU.

8.4.5 Dedicated EVA Hardware Servicing Areas

The lunar base shall provide the following features in the pressurized area in close proximity to the airlocks:

o Storage area containing EVA expendables, spares, EMU resizing components,

o Maintenance area containing workbench, tool storage, microprocessor diagnostic devices,

o EVA and external remote controlled equipment control/display station for operating external equipment (rovers, cranes, baggers), storage and transmission of EVA task data, storage and display of biomedical data on EVA crew, viewing of EVA operations,

- Medical treatment areas,
- EVA preparation area containing shower, toilet, stowage lockers for LCVG, underalls, etc., and
- Means for cleaning exterior of EMU in crew airlock,

The following EVA maintenance support capabilities shall be provided by the lunar base:

- o Draining of condensate from EMU humidity control system,
- o Regeneration/recharge of EMU subsystems; CO2 removal, heat sink, power, O2 supply, and
- o Cleaning and drying of EMU interior.

8.4.6 Airlock Interfaces

Airlock interface requirements have been derived from a study of the design reference mission and are consistent with the requirements for the Space Station airlocks. Preliminary anticipated airlock volumes are shown in Figure 41 and pre-EVA checkout procedures in Figure 42.

In order to reduce further the chance for dust entry into the habitat, a scenario was envisioned which while it requires some additional hardware elements, it may provide significant advantages. This approach is only possible with a back hatch or single opening EMU design. The crew would use the dust room/porch to clean off as much dust as possible, then enter the Crew Lock. The Crew Lock would then be pressurized and checked out to verify the atmosphere. The following procedure would then be followed:

1. The PLSS is covered with a clean shroud that is attached to the perimeter of the PLSS by the crewmember.
2. The crewmember takes a position with the PLSS facing Hatch 1 or 2 (See Figure 41).
3. Hatch 1 and 2 are equipped with a smaller Hatch that, when opened into the Equipment Lock, permits the covered PLSS to be removed.
4. The crewmember attaches the EMU to the perimeter of the smaller Hatch.
5. The PLSS is removed and the crewmember exits from the EMU into the Equipment Lock leaving the suit in the Crew Lock.
6. The smaller Hatch is closed.
7. The EMU is removed from the Hatch 1 or 2 by a crewmember remaining in the Crew Lock and stored.
8. The last crewmember's EMU is left in position attached to Hatch 1 or 2 ready to be used when a crewmember will exit from the Equipment Lock.

The airlock interface requirements are:

- o Airlocks shall include Equipment Locks, Crewlock/Hyperbaric Chambers, Tool Locks, Logistic Locks and Dust Rooms and Porches,
- o All airlocks shall incorporate systems to minimize transfer of dust from the airlock to the Habitat,
- o The <u>Equipment Lock</u> shall permit four crew to go EVA simultaneously. Automated checkout servicing and maintenance (SPCS) equipment (Figure 42), and don/doff stations shall be provided for four EMU's. EVA exit/entry shall occur through the Crewlock (two at a time), or via the Equipment Lock hatch (four at a time). Cleaning equipment shall be incorporated to remove lunar soil/debris from the EMU's and from the inside of the Equipment Lock. In addition, the Equipment Lock shall provide the following internal and external equipment; lights, hard communication links, video cameras and umbilicals, and habitat life support controls and displays,

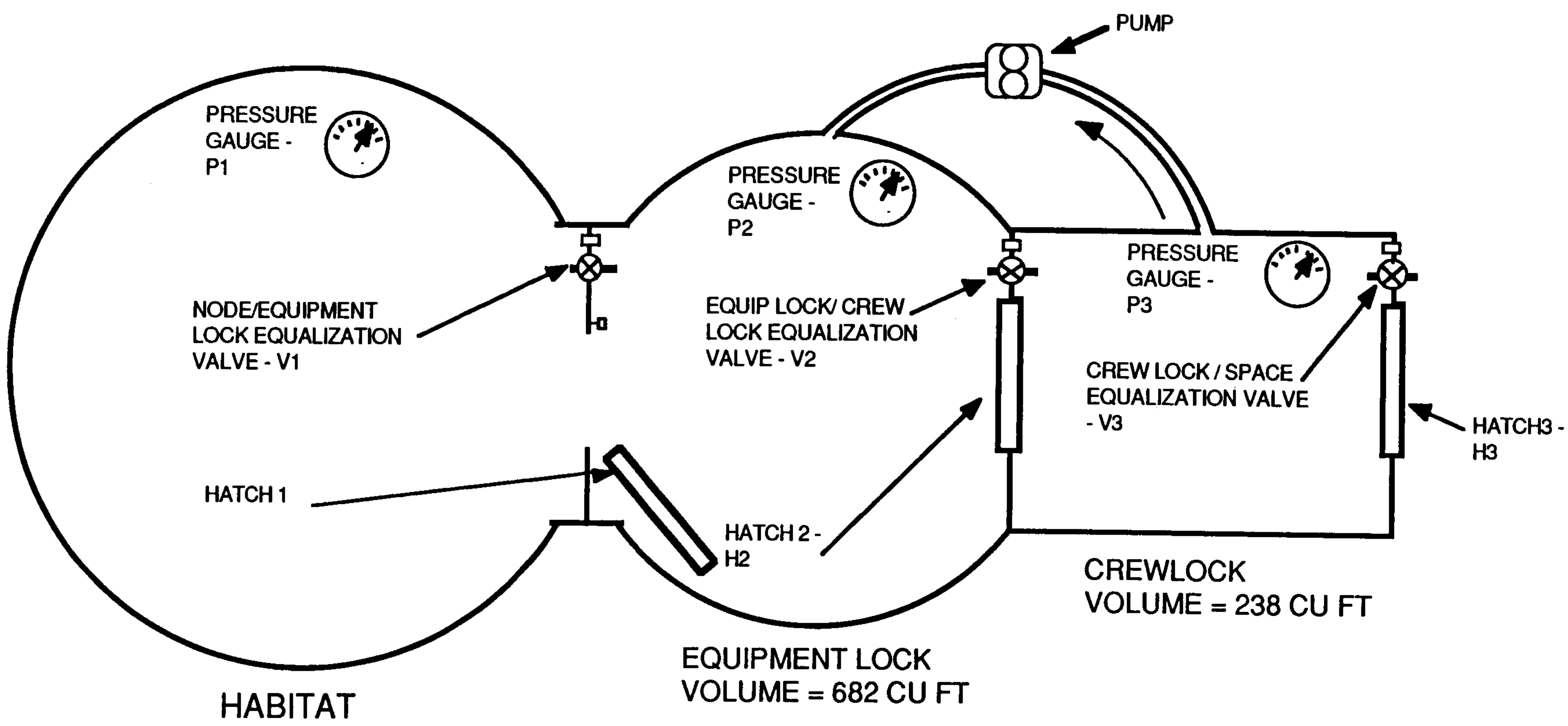


FIGURE 41: BASELINE AIRLOCK SCHEMATIC

AUTOMATIC SERVICING SUCH AS RECHARGE OF EXPENDABLES (E.G., O2, POWER, CO2 ABSORPTION, THERMAL SINK) AND SUIT DRYING. THESE FUNCTIONS SHALL BE PERFORMED ROUTINELY AFTER EACH EVA, AND SHALL BE COMPLETED PRIOR TO THE NEXT EVA.

A RAPID RECHARGE FUNCTION SHALL PROVIDE REDUCED CAPABILITY AFTER 1 HR RECHARGE.

CHECKOUT SHALL BE PERFORMED AUTOMATICALLY (UNDER CREW CONTROL) PRIOR TO EACH EVA, AND SHALL INCLUDE CHECKOUT OF BACK-UP SYSTEMS. OPERATION OF THE AIRLOCK SHALL BE AUTOMATIC (UNDER CREW CONTROL).

AFTER EACH EVA THE SYSTEM SHALL AUTOMATICALLY PERFORM A POST EVA DATA DUMP, AND ANALYSE THIS DATA TO DETERMINE MAINTENANCE ACTIONS. THE SYSTEM SHALL DISPLAY ROUTINE MAINTENANCE REQUIREMENTS, AND SHALL KEEP AN INVENTORY OF MAINTENANCE ITEMS. THE SYSTEM SHALL DISPLAY DATA, SCHEMATICS AND PROCEDURES NECESSARY FOR UNSCHEDULED MAINTENANCE, WHICH CAN BE CALLED UP BY THE CREW.

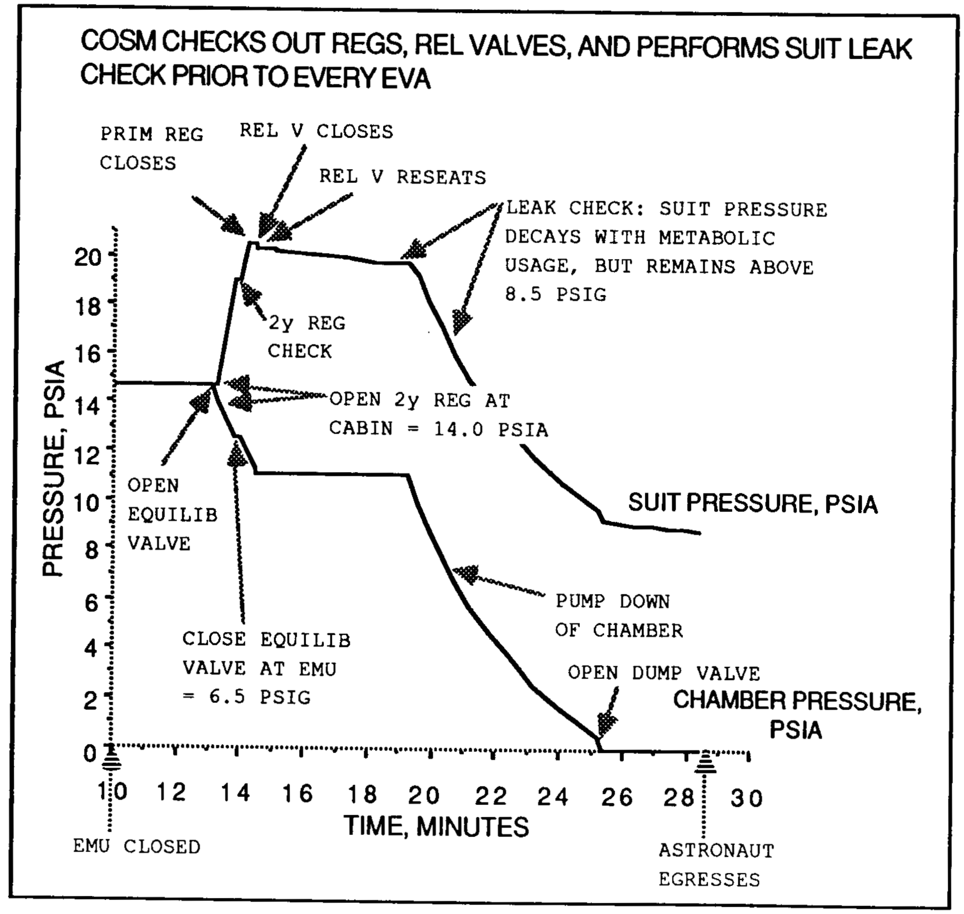


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FIGURE 42: LUNAR EVA SERVICING CHECKOUT AND MAINTENANCE

- The Crewlock/Hyperbaric chambers shall permit two crew to go EVA simultaneously. They also function as a facility for medical treatment of bends or air embolism. Gas storage tanks permit rapid pressurization to 6 atmospheres for this treatment, and medical accommodations are provided for one patient and one attendant. EVA exit/entry in normal operations shall occur through the Crew Lock hatch. Using the Crew Lock reduces the power and consumables expenditures. In addition, this module shall incorporate the following internal and external equipment; lights, hard communication links, video cameras and umbilicals,

- Tool locks shall allow small equipment and supplies to be passed from inside the lunar habitat to an EVA crew. Tool locks shall incorporate external video cameras, lights and communication links,

- Logistic Locks shall allow for large-item logistics transfer and serve as back-up equipment lock. In order to provide redundancy on the lunar surface, they are essentially common with the Equipment Locks and provide the same capabilities. In addition they provide equipment to facilitate logistics transfer, and

- Dust rooms/porches shall provide the facilities for removing lunar soil, debris and dust from the EMU prior to entry into the airlocks. One dust room/porch is located at each external hatch, and shall provide unique equipment for cleaning lunar debris, storage and mounting facilities for disposable/reusable coverings and trash storage. In addition, dust rooms/porches shall provide the following common internal and external equipment; lights, hard communication links, video cameras and umbilicals.

8.4.7 Transportation

Due to potential damage from blowing dust during take-off and landing the loading site will need to be at some significant distance from the base. Requiring the crew to walk there, or to some other site where LRV's would be stored, reduces safety and increases the time associated with these operations. Therefore, remote calling of LRV's is required. This requirement does not eliminate the need for direct crew control, but it improves the overall system capability.

- The analysis of the DRM indicates a requirement for two types of LRV's:

  - The light LRV shall be stored in a shed and called and controlled remotely. It is sized for two crew plus a small amount of supplies and portable life support equipment. In emergencies it shall be used by four crewmen, and

  - The heavy LRV which shall be stored in a shed, called and controlled remotely and shall provide transportation for four crew and equipment. It also shall provide light construction capabilities through attachments. It shall include: lights, communication, navigation, and extended life support capability. Its capability is expanded through use of attachments such as: a cherry picker, a front end loader, a tool caddy, a fork lift, a winch, and a simple robotic/teleoperated arm and end effector. To assist in heavy operations it shall be capable of being anchored.

- The DRM also requires a lander and an ascent stage for use in an emergency to transport the four crew and four suits to the lunar surface. The lander shall support four crew for the time necessary for set-up of the base (1-2 days plus contingency), provide communications, and have a dust room/porch.

8.4.8 Other

The other systems required by the DRM which have interfaces with the EMU are the habitat, tool shed, construction equipment and quonset hut/shielding.

The habitat is a pressurized module designed to support four crewmembers for up to three months. It includes the following EVA accommodations: a workbench, a repair area, an EVA storage area for spares and consumables, dust collection/cleaning technology, a data management system and control console, a remote equipment console, communications, and an EVA monitoring station.

The tool shed is used to store tools and equipment for the period of time when they are not in use. It is located outside of the quonset hut near the entry tunnel. It is not pressurized and shall provide; lights, storage bins or areas, work tables, dust cleaning equipment, power, communications and a video camera.

The purpose of the construction equipment is to assist in mating of modules, assembly of structures, and construction of shielding. It shall provide controls compatible with EVA crew, be EVA-maintainable, restraints and handholds as necessary. It may include: an automated soil bagger, hoisting equipment, a simple fetch-it robot, and a general purpose crane with interchangeable end-effectors.

The quonset hut is intended to support the shielding and provide access to the habitat. The shielding will be composed of lunar soil in bags and be 2 to 3 meters thick. It shall provide: lighting (artificial and natural), a floor which shall be prepared to have minimum surface dust, video cameras, and two entrance tunnels which provide radiation shielding and are wide enough to permit equipment entry (See Appendix 1).

9.0 HARDWARE CAPABILITIES ASSESSMENT

9.1 Technology Needs

To determine whether the current or developing EVA technology would fulfill lunar AEVA requirements, an assessment of present and near-term EVA technology was performed. Data for this assessment was collected from previous studies and from TAG members. They were organized to enable a comparison of the Shuttle and Space Station (under development) technology to the human capabilities. These comparisons are shown in Table 3 to 5 and address:

- o Range of Motion and Torque, and
- o Parameters, and
- o Weight and Volume.

The human data describes 50th percentile female and 95 percentile males. The torque values for the suited cases are the torques required to move the joint in question. The Space Station values are design goals set by the measured performance of the STS system. In theory, to compare the human torques (where available) to the suited torques, the suited maximum torque should approach the human torque minus the torque required to move the joint. Test results to verify this hypothesis have not been published, so these values should be considered a guideline. In many cases data which could be directly compared to suited data was not available, specifically little information regarding human torque capabilities was found.

Based on the review of the requirements, eight technology areas were assessed where current or developing technologies do not satisfy the requirements identified:

- o Gloves,
- o Suit design for walking comfort,
- o PLSS,
- o Bearings and dust seals,
- o Dust cleaning methodologies and tools,
- o Design of habitat and suit/habitat interfaces to prevent dust infiltration,
- o Suit materials to minimize dust pick-up and static charging, and
- o Visors.

Suit atmosphere and pressure will also have to be established to obtain optimum performance during EVA. In addition supporting system technology areas requiring development and/or transfer were identified:

- o Robotics/Teleoperation,
- o Communications, and
- o Rescue/Medical.

9.1.1 Gloves

The space suit glove designs currently being used on the Space Shuttle are greatly improved compared to earlier suit gloves, but they still have limited finger mobility. This limitation is due in part to the lack of a finger metacarpal joint in the glove. It induces early fatigue and limits the power grip strength. Despite this drawback, the performance of this glove has been acceptable in

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TABLE 3: COMPARISON OF HUMAN AND SUIT RANGE OF MOTION

	Range (deg)			Max. Torque (in-lbs)		
	STS	HUMAN	SSP	STS	HUMAN	SSP
Shoulder Mobility						
Adduction/Abduction	150	182	135	100	N/A	100
Lateral/Medial	150	131	135	150	N/A	150
Flexion/Extension	180	249	180	70	N/A	70
Elbow Mobility						
Flexion/Extension	130	142	130	50	N/A	50
Wrist Mobility						
Supination/Pronation	180	190	180	6	154	6
Flexion/Extension	120	189	120	6	N/A	6
Abduction/Adduction	90	74	90	6	18	6
Waist Mobility						
Flexion/Extension (waist and hip/thigh combined)	90	N/A	100	400	N/A	400
Rotation	150	N/A	N/A	50	N/A	N/A
Hip Mobility						
Flexion	70	113	40	50	N/A	50
Abduction	10	53	10	600	N/A	600

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TABLE 3: COMPARISON OF HUMAN AND SUIT RANGE OF MOTION (Continued)

	Range (deg)			Max. Torque Req. (in-lbs)		
	STS	HUMAN	DEV	STS	HUMAN	DEV
Knee Mobility						
Standing Flexion	120	113	120	130	N/A	130
Kneeling Flexion	150	159	150	N/A	N/A	N/A
Ankle Mobility						
Flexion/Extension	80	73	80	70	N/A	70
Glove Mobility						
Finger (Flexion/Extension)	~90°	~90°	80-90°	3.5*	N/A	5.5
Fingers (Ability to comfortably grasp and hold a rod for 5 min)	1.0" dia	0.25 dia	0.5" dia	N/A	N/A	N/A

Source Human Data: Woodson, W.E., Human Factors Design Handbook, McGraw-Hill, 1981.

Design Study of a Prototype Anthropomorphic Robotic Hand For Use with an Extravehicular Space Suit, prepared by Arthur D. Little, NAS9-17454, 1986.

Source: Suited Data: NASA-STD-3000, ILC Dover, NASA JSC (glove data)

* Unmanned

Note: All values are average ranges added together, or maximum observed torques.

TABLE 4: COMPARISON OF SUIT PARAMETERS AND REQUIREMENTS

	STS	SPACE STATION
Lower Torso Assembly (LTA)		
Sized to fit women	5th %ile to 95th %ile	50th%ile to 95th%ile
Sized to fit men	5th %ile to 95th %ile	5th%ile to 95th%ile
Operating Pressure	4.3 Psig (29.6 kPag)	8.3 Psig (57.2 kPag)
Leak Rate (standard cm³/minute)	46.5 SCC/m 0_2 operating in vacuum @ 4.3 psig (29.6 kPag)	18 SCC/M O_2 operating in vacuum @ 8.3 psig
Weight	38 lbs (17.2 kkg)	71 lbs (32.2 kg)
Upper Torso		
Gloves		
Operating Pressure	4.3 Psig (29.6 kPag)	8.3 psig (57.2 kPag)
Leakage (standard cm³/min)	3 SCC/m 0_2 operating in vacuum	3 SSC/m 0_2 operating in vacuum
Waste Disposal		
Men: Urine Collection Device (UCD)	950 cc capacity	1000 cc capacity
Women: Disposable Absorbent Containment Trunk (DACT)	950 cc capacity	1000 cc capacity
Feces	No Provision	TBD
Vomit	No Provision	TBD
Food	210 kcal (833.7 Btu)	750 kcal (2975 Btu)
Water	20 oz (0.59 L)	40 oz (1.18 L)
Visibility	NASA-STD-3000 Section 14.3.4.4	NASA-STD-3000 Section 14.3.44

TABLE 5: WEIGHT AND VOLUME COMPARISON

	STS	SPACE STATION
PLSS Weight	200 lbs (90.7 kg)	430 lbs (195 kg)
PLSS Volume	3.2 ft^3 (0.09 m^3)	5.4 ft^3 (0.153 m^3)
Suit Weight (w/TMG)	165 lbs (74.8 kg)	214 lbs (97.1 kg)
Total Suit & PLSS Volume	16.2 ft^3 (0.459 m^3)	22 ft^3 (0.623 m^3)
Battery Weight	10 lbs (4.54 kg)	30 lbs (13.6 kg)
Battery Volume (Silver Zinc)	200 in^3 (3277 cm^3)	518 in^3 (8488 cm^3)
Sublimator Weight (w/10 lbs H_2O)	12.5 (5.67 kg)	N/A
Sublimator Volume (w/o water)	345 in^3 (5654 cm^3)	N/A
Wax Radiator Weight	N/A	160 lbs (72.6 kg)
Wax Radiator Volume	N/A	1.75 ft^3 (0.0496 m^3)

Note: Compiled from TAG provided data which may be different from ZPS requirements document

current tasks performed with the suit at an operating pressure of 4.3 psig. At increased pressures, such as the 8.3 psig proposed for the Space Station, the anticipated performance would decrement and probably make this glove unacceptable.

NASA JSC and NASA Ames Research Center have been funding various glove development projects. These programs have demonstrated the great potential for improvements using these approaches, and, within 5 to 10 years are likely to produce gloves (or analogous systems) which meet the lunar DRM requirements for dexterity, mobility, tactility, and fatigue. However, the endurance life and wear resistance of these gloves and systems indicate that they will not meet the lunar requirements without further development. Gloves should be classified as limited life items. Experience has shown that gloves will require routine and periodic maintenance and refurbishment to ensure glove system serviceability.

Assessing the dexterity of an individual wearing protective gloves is not straight forward. Dexterity is a function of the thickness, material (elasticity), and fit of the glove, where fit seems to be a driving factor. A difference of 5 mils in thickness does not cause a measurable decrement in dexterity unless additional confounding factors, such as fit and material stiffness changes are present. Generally, regardless of the fit and stiffness, 10 mils thickness change causes a detectable difference in dexterous performance.

Various standardized tests have been employed to assess the performance differences between various gloves and the bare hand. In a recent study conducted by Mond, et al., analyses of the effect of thickness on dexterity indicated that a 5 mil natural rubber latex glove provided dexterity comparable to that of the bare hand. Various other glove types were also tested to explore the singular and interactive effects of thickness, fit, and material. For example, 25 mil thick natural rubber latex, neoprene/natural rubber blend and nitrite - were compared to the bare hand, 5 mil and 10 mil thick natural rubber latex gloves. The results of one of the standardized dexterity tests indicated a 40% performance descrement from bare hand dexterity for the 25 mil gloves. This performance decrement increased to 50% in two of the other tests due to the increased tactile sensitivity and five finger dexterity required to successfully execute these tests. Therefore, it can be concluded that even if pressurized suit gloves improve greatly (approaching other non-pressurized protective gloves) when the mission scenario requirements expand to include more dexterous tasks, alternate technologies must be developed to improve hand function beyond that possible with any gloves.

9.1.2 Walking Comfort

The main elements of walking comfort are joint range of motion, required torque, suit conformance and compliance, and bulk. The design of the joint has a significant influence on these factors. The Apollo suits used dipped convolutes, a molded joint which had limited mobility, particularly at the hip. It was concluded that this limitation was the cause of the very stiff legged gait observed when crewmembers walked. The Shuttle Space Suit Assembly (SSA) uses flat pattern and tucked fabric joints that have significantly improved performance without increasing bulk. These joints still require significant torque to actuate. The advanced suits (ZPS, AX-5) employ multi bearing joints that greatly improve mobility while adding some bulk. Current programs are aimed at reducing bulk and further improving range of motion. In addition the range of motion for 0-g is aligned to correspond to 0-g motions which are not the same as the "loping" gate experienced in 1/6-g. Improvements are expected as a result of these efforts, but as the 0-g requirement is not as stringent as the 1/6-g which has more significant chaffing potential, some additional efforts may be required. Therefore, it was concluded that effort should be devoted to quantifying the general comfort needs associated with 1/6-g activities to determine how significant the suit development requirements are in this area.

9.1.3 PLSS

The primary requirement for a PLSS is that its size and weight in 1/6-g should be compatible with standards for back-mounted equipment. Combined with the need for better thermal control, an improved PLSS is required for long-duration lunar missions. The two major elements that impact the ability of a design to meet these requirements are the thermal control and power systems.

The Shuttle sublimator was designed to be small and light, weighing just 2.5 lbs.(1.13 kg) and occupying 345 in^3 (5654 cm^3). In addition an average EVA required 10 lbs. (4.54 kg) of consumable water, and the EMU provided storage for this water. The wax radiator is a regenerable system which pays a significant penalty in terms of size and weight (160 lbs (72.57 kg) and 1.75 ft^3 (49,560 cm^3)). While a sublimator system seems attractive from a size and weight standpoint, the availability of water on the lunar surface is in question. The environmental impact of venting water is small but may affect some experimental measurements, e.g. solar spectrum changes. On the other hand a 53 lb (24 kg in 1/6-g) mass penalty for a non-venting system would be unacceptable if back-mounted. The weight and volume of a power system for a regenerable PLSS would be significant using existing technology.

The efficiency and effectiveness of thermal control links the dissipation of heat with the requirement for power. The EMU subsystems that govern this relationship are the LCVG and the automatic thermal control system. It is possible to envision an LCVG design which would distribute the cooling more effectively, make control system response more rapid, and thus avoid overshooting the required cooling/heating. These improvements would in turn reduce the amount of heat dissipated and the power demand reducing system size and weight. To improve the power density of the power system, technological innovation and a significant investment would be required. However, the long lead time to mission launch, combined with the requirement in other systems (both within NASA and outside) for further improvements, will stimulate technological innovations. Therefore, the evolution of these technologies should be monitored and technology improvements transferred wherever possible.

In order to achieve a small and lighter PLSS, a systems design incorporating all of these elements should be utilized. As it is a major suit system and is significantly different from current development plans, it should be targeted as a priority.

9.1.4 Bearings And Dust Seals

It was noted by the Apollo crews that after three days, the upper arm bearings and wrist disconnects were notably more difficult to move because of dust penetration into the joints. Although the current technology provides dual seals and environmental seals which would reduce this problem, they are designed for the space environment, not the lunar surface. Lunar dust is a fine material which adheres easily and is charged. To date space suit programs have not been required to successfully perform in such a dusty environment for 40 to 60 days. Therefore dust seals and suit bearings are a primary concern.

In addition equipment must be designed to function in the harsh lunar environment. Unlike the EMU, which may need to be used by the crew for EVA on the return mission, equipment systems will not be returnable to Earth after each mission for refurbishing and repair. Many of these systems will have to be used throughout the life of the base. Therefore, bearing and sealing technologies for lunar equipment, power tools, and vehicles are also major concerns.

9.1.5 Dust Cleaning Methodologies And Tools

In addition to making lunar equipment as resistant to dust as possible, equipment must be cleaned to limit transfer of dust into the habitat. The interior, unshielded portions of equipment must also be cleaned during module changeout or repair. The more effective the dust cleaning methodologies and tools, the less stringent the constraints on the design on the individual systems and the longer

the system life. As discussed in the environmental description (Section 7.0), lunar dust (soil) has an irregular shape which promotes adhering to other items and it is often charged. Therefore, it was concluded that cleaning equipment which provides easy access to all surfaces of an object is necessary, and that multiple levels of cleaning systems should be employed.

Despite the best efforts of the EMU, equipment, and habitat designers, some dust will also be introduced into the habitat. Therefore cleaning methodologies will be required for both EVA and IVA. These procedures will have to be performed often and should be designed to require the minimum amount of crew time possible. Although the military has developed equipment for operation in a desert environment, operation of the EMU on the lunar surface may be more demanding because of the combination of a dusty environment, charged particles, and vacuum. Failure to provide a workable system will have a significant impact on lunar surface operations and hardware designs. Therefore dust cleaning methodologies are an important development area.

9.1.6 Habitat And Habitat/Suit Interfaces For Dust Environment

It was concluded that some dust will enter the habitat. Therefore, the habitat systems and layout must be designed so as not to affect the hardware used in the habitat or jeopardize operations or life support.

9.1.7 Suit Materials

The outer layer of the current Shuttle EMU TMG is a blend of Teflon, Nomex and Kevlar. This formulation was optimized based on mobility, abrasion resistance, and endurance life. For Space Station, the addition of a chemical barrier to this layer is anticipated. The addition of this barrier may alter the insulation properties of the multilayer insulation by requiring longer times to reach vacuum between the layers. This issue will be resolved during the Space Station development programs.

Further development will be required for lunar EVA activity. Two major parameters to be addressed will include lunar dust pick-up and endurance limits. The effects of dust and lunar EVA scenarios on life of the garment will require investigations to optimize this component for lunar activities.

9.1.8 Visors

Shuttle EMU visors consist of three subassemblies: a clear protective visor, a gold sun visor and three opaque eye shades. The visual characteristics of these assemblies are optimized for the LEO environment and Shuttle operational scenarios. For lunar activities two concerns relative to visor performance, will require further investigation. Durability of the outer visor surfaces in the presence of lunar dust may be a problem. The second concern is that of visual acuity on the lunar surface. Due to stark shadows and the need to enter and exit very dark and very bright areas, approaches to improve visual acuity will require investigation, including the provision of a helmet mounted variable direction "miner's lamp", or a variable quick changing sun visor.

9.1.9 Robotics/Teleoperation

In the DRM the need for several robotic or teleoperated systems was identified. A robotic device is a general purpose system which can autonomously (without human supervision) perform a variety of tasks when commanded. A teleoperated device is a system which is controlled by a human from a remote location. The location could be a few meters away or many kilometers. A crewmember could control a piece of equipment in several ways, depending upon the sophistication of the device. For example, a teleoperated device could receive directions from a control station located on or near the device, from inside the habitat, or from a vehicle on the surface or in orbit. Automated equipment is defined as special-purpose hardware which can perform a particular task (such as bagging) without supervision. The state-of-the-art in these technologies is rapidly evolving due to the many earth and space applications. Many of these technologies are sufficiently mature to be applied to lunar

equipment or will be by 2005. There are even developments for equipment that will function in dusty or high radiation environments (e.g., mines or contaminated nuclear power plants). It was concluded that assessing the degree of technology readiness and the operational impact of their availability will be crucial to mission planning. Due to the repetitive and hazardous nature of many of the EVA tasks, these technologies will be mission-enabling technologies and will require further development.

9.1.10 Lunar Surface Communications

EVA crew will not always be within each others' line-of-sight, nor will there be an unobstructed line with other key communications sites when operation behind hilly terrain or in a crater. On the moon there is no atmosphere to cause radio transmissions to be reflected back to the lunar surface by an ionosphere. The study concluded that existing technology can be applied and the relationship of range of operations with relay station (orbital or surface) placement established to meet safety and redundancy concerns.

9.1.11 Rescue/Medical

Most of the requirements for rescue/medical can be met by existing or developing technology. However, a study of the unique injury modes and types associated with the lunar environment should be made. In addition, one issue requiring specific hardware study/development was identified. For example, if an accident occurred during EVA in which in-suit bleeding resulted, the affects on PLSS could be catastrophic. Rescue/medical procedures/hardware need to be developed if such injury could be a possible occurrence.

9.2 Technology Development Plan

From the areas identified as requiring technology development two were selected which have both long lead times (> 5 years) and significant unique lunar requirements: PLSS and dust. The dust area encompasses the issues in Sections 9.1.4, 9.1.5, and 9.1.7, as it was concluded that technology development will be most productive if these were considered together.

9.2.1 PLSS

As mentioned in Section 9.1.3, the two primary areas of concern are thermal control and subsystem power. Study/technology development in each of these areas must occur prior to their integration into a new PLSS.

9.2.1.1 Thermal Control

The thermal control issues can be divided into gaining an understanding human heat transfer in the lunar environment and developing hardware concepts that can meet the size and weight constraints and still provide effective cooling/heating. To develop a thermal control subsystem, a three-phase program is recommended.

Phase I: Analytical Study

Objective: To develop an in-depth understanding of the human thermal balance within the constraints of the lunar environment and an improved LCVG, and new data on comfort levels while working in encapsulating clothing. In addition it will be necessary to quantify the load and profile of backmounted equipment for different crew (male/female, large/small), and to analyze the viability of non-backmounted or reduced capacity options.

Duration: 8-12 months

Budget: $100,000 to $200,000

Phase II: Concept Development

Objective: In light of the detailed requirements and data generated in Phase I, to develop an array of concepts which will fulfill these requirements, perform laboratory investigations necessary to prove concept feasibility, and select a preferred concept.

Duration: 6-9 months

Budget: $250,000 each award (multiple awards, minimum 2)

Phase III: Breadboard System Development

Objective: To take the concept from the selected contractor and develop a full breadboard system including an LCVG and conduct system performance tests.

Duration: 12-18 months

Budget: $800,000 to $1M

9.2.1.2 Power Supply

The power supply is a significant portion of the PLSS weight and volume. To reduce the size of the power supply without compromising on capacity, advanced technologies beyond the state-of-the-art are required. The advanced power supply technologies will need significant funding. Therefore it is recommended that once a concept for the thermal control system is identified, a study to fully define the PLSS power requirements and identify relevant existing or developing technologies should be undertaken. The program should be divided into two phases: an analytical study phase and an ongoing technology monitoring/requirements modification.

Phase I: Analytical Study

Objective: To quantify the subsystem power requirements considering existing technology for oxygen and carbon dioxide, sensors, and the selected thermal control concept. To identify nominal and worst cases for operating conditions, and to identify technologies capable of meeting these requirements within size and weight constraints.

Duration: 10-12 months

Budget: $100,000 to $150,000

Phase II: Technology Monitoring/Requirements Modification

Objective: To keep abreast of technology as it evolves, evaluate the impact of the evolving lunar mission requirements and constraints on the PLSS and make a final determination as to whether the technology will fulfill the requirements.

Duration: 3 years

Budget: $50,000 to $75,000 per year

9.2.1.3 Integration/Development

Once a thermal control subsystem breadboard is available, a program to begin the systems integration/development process can begin. It is recommended that this program be a multiphase effort program resulting in a flight qualified PLSS. This program can begin when Phase I of the power system program is complete and will result in a full PLSS test bed in 3 years, concurrent with the final decision on the power supply. The first three phases will overlap to some degree, and will correspond to an advanced development type program.

Phase I: Study

Objective: To integrate the results of the thermal control program and the power study along with developing subsystem concepts based on available technology for the remaining subsystems to yield a PLSS system concept which meets the performance, size and weight requirements. This program may include laboratory experimentation to the extent required to prove system feasibility.

Duration: 9-12 months

Budget: $500,000

Phase II: Breadboard Development:

Objective: To design, develop, and integrate a breadboard test bed for a complete PLSS using the hardware from the thermal control program and the new subsystems developed in Phase I. This hardware should be used to test the system performance and to identify issues requiring further development, analysis, or study prior to finalizing and detailing a design.

Duration: 18 months

Budget: $1M

Phase III: Prototype Development

Objective: To complete the detailed design for the PLSS and build a prototype that has the form, fit, and function of the final system. This system will then be tested in 1-g and simulated 1/6-g environments to verify performance and operational/human factors feasibility.

Duration: 18-20 months

Budget: $2M

After these programs are completed a program to develop flight qualified hardware can begin. This program would be approximately 4 to 5 years in duration and will include experimental use in lunar sortie and/or space missions.

9.2.2 DUST

The program to develop systems compatible with the lunar dust environment has three phases: advanced development, lunar flight experiment, and a flight- qualified hardware program. In this plan, only address the advanced development program is addressed. The program has been divided into three functional areas: bearings and seals, materials, and cleaning. Each of these areas will have its own program with the following tasks:

o	Requirements Development	4 Months
o	Concept Definition & Trade Studies	5 Months
o	Detailed Design	6 Months
o	Breadboard and Test	8 Months
o	Optimize Design	6 Months
	Total	29 Month

The budgets will be:

o	Bearings and Seals	$600K
o	Materials	$400K

o	Cleaning	<u>$1M</u>
	Total	$2M

The results of these studies will be utilized to design a flight experiment whose objective is to verify the performance of these elements which will form the building blocks of the advanced lunar EMU and related equipment.

9.3 <u>Additional Physiological, And Operations Studies</u>

During the study, a number of scientific, physiological, and operations issues requiring further investigations were identified. These issues have been organized into the requirements areas from which they were derived:

- o Mission Operations,
- o Man/Machine and Physiological/Medical, and
- o Hardware.

The following sections outline these areas.

9.3.1 Mission Operations Derived Studies

Analysis of methodologies for establishing mission tasks and schedules

Operational study of PLSS configuration

Advanced missions feasibility of LRV with a pressurized cab

In-suit bleeding containment

Logistics analysis to trade-off between endurance life and spares

Communications relay for out of line-of-site operations

9.3.2 Man/Machine And Physiological Medical

Approaches to making lunar EVA psychologically acceptable

Long-term effects of elevated PO_2

In-depth analysis of the influence of work/rest cycles on productivity

Simulated 1/6-g walking studies for required range of motion

Backmounted equipment limits and suggested design requirements

Potential of automation and robotics for improving crew productivity

Cooling/heating system sizing for metabolic rate range optimization

Carbon dioxide influence on bends

Heat transfer optimization to reduce thermal control system size/weight

Washable LCVG which inhibits bacterial growth

Size, gender, work rate relationship to urine produced

Work rate, cooling/heating rates, sweat, and their relations to urine produced

Low-residue liquid nutrients and other nutritional alternatives

Food-dispensing technology

The effects of treatment delays, especially hyperbaric

EVA injury scenario analysis to derive additional medical kit requirements

Operational issues concerning habitat/suit pressure within physiological constraints

9.3.3 Hardware

Cost/benefit analysis of 10-year life versus shorter operational life

Study lunar externally-induced loads, impacts, and abrasion

Detailed analysis of tools

Effects of landing near habitat

Development of methodologies for assessing fit, dexterity, tactility, and fatigue

Abrasion data on lunar soil against candidate materials

Accident scenarios to determine realistic values for cut and penetration with lunar environment

Real data collection on micrometeoroids and debris

9.3.4 Recommended Studies

From study issues two important areas for additional work can be derived: lunar environmental and missions operations.

Lunar Environmental Studies

Although there is a large amount of data available on the geotechnical and other physical properties of lunar soil, there is a little information on environmental parameters significant to a long-duration EVA mission on the lunar surface.

Two studies which could provide the data necessary to guide engineering design of EVA-related hardware, to meet some of the requirements identified in this study are:

- Micrometeoroid impacts on materials over periods of time measured in months or years need to be investigated. Space suit and visor candidate materials should be exposed to obtain data on important effects which would permit material selection/development.
- The space radiation environment on the lunar surface has not been adequately characterized over an extended period of time to establish the effects of SEP's and GCR on materials and living organisms. Sensors should be installed at various locations to obtain data on the radiation that reaches the lunar surface. In addition the effects of various amounts of candidate shielding materials should be determined. Finally, the time available to take protective measures after onset of a solar flare event has been detected should be established to a higher level of certainty.

Mission Operations Study

When considering long-duration missions on the lunar surface, such as the DRM or mining of lunar resources, many unresolved operational issues arise. Many of these operations, if performed manually, will be tedious and could be hazardous. Therefore detailed mission planning to avoid repetitive tasks combined with a high level of automation is necessary. In addition the operational issues of conducting routine EVA's in support of mission objectives will have a large effect on the hardware. Therefore an analysis should be undertaken prior to selecting final EVA system

configurations and starting programs to develop associated hardware and tools. These studies, if begun early, can formulate experiments to be performed during sortie missions which will establish the data base and viable options necessary for planning long- duration missions.

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Appendix 1

Lunar Base Configuration for DRM

Sample Calculation

In the following example, we have chosen values for the input variables based upon current hardware capabilities (ie. Shuttle cargo hold dimensions), scientific data (Galactic radiation, Solar flare data, Lunar soil density, etc.), and where necessary, used our best estimate from an engineering standpoint. One of the more important points is that we chose the structural shape of the protective enclosure to minimize the surface area which needed to be covered with Lunar soil. This consideration led to the choice of a shape made up of a cylinder with spherical end caps, over the alternative of some section of a sphere. This selection greatly reduced the surface area of the enclosure for the particular station layout pictured in the figures . These values are for demonstration only, and should not be construed as recommendations for future Lunar outposts.

The conformal entrance/exit tunnel shape chosen achieves the primary objective of reducing the total surface area requiring cover, and also provides many other attractive features. The most important aspect of this concept is the ability to provide totally effective radiation shielding by maintaining a minimum of 2 meters of Lunar soil between any point within the enclosure and any point outside of it, without making the tunnel difficult to negotiate with a rover type vehicle or, requiring the use of a door. All other tunnel concepts we examined either had a significantly larger area to cover, or the presence of very sharp (almost 90°) bends which would be very difficult for a rover to maneuver through. The last advantage of this tunnel concept is that it would provide an emergency radiation shelter capability very early in the excavation and burial process.

Using the following values for input variables as defined in table 1 in conjunction with the equations defined in table 2 we have developed the following estimate for the task of covering the Lunar base described in figures 1 and 2 to a depth of 2 meters with Lunar soil.

For the baseline habitat pictured in figure 2, we have chosen the following values.

$L_h = 18.25\,m$

$D_{ll} = 7m$

$D_{el} = 7m$

$L_{cl} = 3m$

$L_p = 3m$

$W_p = 3m$

From equations 1,2 we get the size the overall structure as;

$W_S = 10m$

$L_S = 38.25\,m$

Providing a clear walkway which is a least 3 M wide at all points and using equations 3 and 4 gives us the interior dimensions of the enclosure

$L_E = 44.25\,m$

$W_E = 16m$

Equation 5 now provides us with the radii of the cylinder and the spherical end caps

$R_{CE} = 8m$

Equation 6 then provides the length of the cylindrical portion of the enclosure.

L_C = 28.25 m

Plugging these results into equations 7 and 8 tells us the volume of Lunar soil needed to cover the enclosure (less tunnels) to a depth of 2 meters

V_{SS} = 1022 m^3

V_{SC} = 1598 m^3

Next we use equations 9 and 10 to determine the entrance/exit tunnel dimensions required to clear a passage way 3m tall by 3m wide

R_T = 2.12 m

L_T = 25.3 m

Using equation 11 now gives us the additional amount of soil required to cover each tunnel to a depth of 2 m

V_{ST} = 969 m^3

Using two entrance/exit tunnels, equation 12 gives us the total for the entire installation

V_T = 4558 m^3

For a bag volume of 2 m^3 the number of bags required is now determined from equation 13

N_B = 2279 bags

Using data for EPA workers bagging contaminated soil while wearing fully encapsulating chemical protective clothing as a baseline, we have made the following estimates for work rates

R_{bm} = 10 bags per Hour

R_{bh} = 5 bags per Hour

R_{pm} = 12 bags per Hour

R_{ph} = 8 bags per Hour

Assuming that the machinery is operated manually only 10% of the time, and that it still must be watched while operating automatically, equation 14 gives us the total number of man-hours spent bagging Lunar soil.

T_B = 240 man-Hours

The total number of man-Hours associated with moving bags from the excavation site to the enclosure site is estimated for a round trip time of .2 Hours and a load of 4 bags per round trip with equation 15

T_M = 115 man-Hours

Assuming that 85% of the filled bags can be placed by the automated machinery, and that an operator is still required to oversee the operation, equation 16 now provides the total number of man-Hours spent placing bags upon the enclosure

T_P = 200 Hours

These numbers may now be plugged into equation 17 to determine the total number of man-Hours required to cover the entire installation

$$T_{MH} = 555 \text{ man-Hours}$$

If we have 4 workers available and each one works one 6 hour shift per day, then equation number 18 gives us the total number of days to complete the task.

$$T = 23 \text{ days spent on covering the installation.}$$

Table 1

Input Variables (MKH units unless noted otherwise)

L_h	=	Length of habitat module
D_{ll}	=	Diameter of logistics lock
D_{el}	=	Diameter of equipment lock
L_{cl}	=	Length of crew lock
L_p	=	Length of dust room/porch
W_p	=	Width of dust room/porch
L_r	=	Length of ramp
W_r	=	Width of ramp
W_w	=	Width, at minimum clearance, of walkway between habitat and enclosure structure
H_t	=	Height, at minimum clearance, of entrance/exit tunnel
W_t	=	Width , at minimum clearance, of entrance/exit tunnel
N_t	=	Number of entrance/exit tunnels in enclosure
d	=	Depth of soil covering shelter
ρ_t	=	Density of soil used for covering shelter
R_{bm}	=	Rate of soil bagging by machine (bags/Hour)
R_{bh}	=	Rate of soil bagging by humans (bags/Hour)
R_{pm}	=	Rate of bag placement upon enclosure by machine (bags/Hour)
R_{ph}	=	Rate of bag placement upon enclosure by humans (bags/Hour)
$\%_{fm}$	=	Percentage of bags filled by machinery
$\%_{fh}$	=	Percentage of bags filled by humans
$\%_{pm}$	=	Percentage of bags placed upon enclosure by machinery
$\%_{ph}$	=	Percentage of bags placed upon enclosure by humans
V_b	=	Volume of each bag (M^3)
T_{rt}	=	Time to complete a round trip from bagging site to enclosure with load of bags
N_{rt}	=	Number of bags which can be carried/round trip
N_w	=	Number of workers available for project
S_d	=	Number of shifts that each person is expected to work per day
T_s	=	Time actually spent working on each shift

Table 2

Calculated Values

Largest value of width of pressurized habitat

1) $W_S = D_{ll} + W_p$ or $= D_{el} + W_p$

Overall length of pressurized habitat

2) $L_S = D_{ll} + L_h + D_{el} + L_{cl} + L_p$

Length and Width of protective enclosure, at ground level

3) $L_E = L_s + 2W_w$

4) $W_E = W_S + 2W_w$

Radii of cylindrical and spherical components of protective enclosure

5) $R_{EC} = \frac{W_E}{2}$

Length of cylindrical component

6) $L_C = L_E - 2R_{EC}$

Volume of Lunar soil required to cover spherical portions of protective enclosure

7) $V_{SS} = \frac{2}{3}\pi\left[(R_{EC} + d)^3 - R_{EC}^3\right]$

Volume of Lunar soil required to cover cylindrical portion of protective enclosure

8) $V_{SC} = L_C\frac{\pi}{2}\left[(R_{EC} + d)^2 - R_{EC}^2\right]$

Minimum radius which allows object H_t tall by W_t wide to clear entrance/exit tunnel walls

9) $R_T = \frac{\sqrt{H_t^2 + W_t^2}}{2}$

Length of entrance/exit tunnel, along it's center-line

10) $L_T = \frac{\pi}{2}(2R_{EC} + d)$

Additional volume of Lunar soil required to cover entrance/exit tunnel

11) $V_{ST} = L_T\left\{\frac{\pi}{4}\left[(R_T + d)^2 - R_T^2\right] + \frac{d}{2}(H_t + W_t)\right\}$

Total volume of Lunar soil required to cover entire installation

12) $V_T = N_t V_{ST} + V_{SC} + V_{SS}$

Total number of soil bags needed to cover entire installation

13) $N_B = \frac{V_T}{V_b}$

Table 2 cont.

Total number of hours spent bagging Lunar soil

$$14)\quad T_B = \frac{N_B}{\%_{fm}R_{bm} + \%_{fh}R_{bh}}$$

Total number of hours spent transporting filled bags from excavation site to enclosure site

$$15)\quad T_M = \frac{N_B}{N_{rt}}T_{rt}$$

Total number of hours spent placing filled bags upon enclosure

$$16)\quad T_P = \frac{N_B}{\%_{pm}R_{pm} + \%_{ph}R_{ph}}$$

Total number of Man-Hours spent on covering installation

$$17)\quad T_{MH} = T_B + T_M + T_P$$

Total number of days required to complete task

$$18)\quad T = \frac{T_{MH}}{T_s N_w S_d}$$

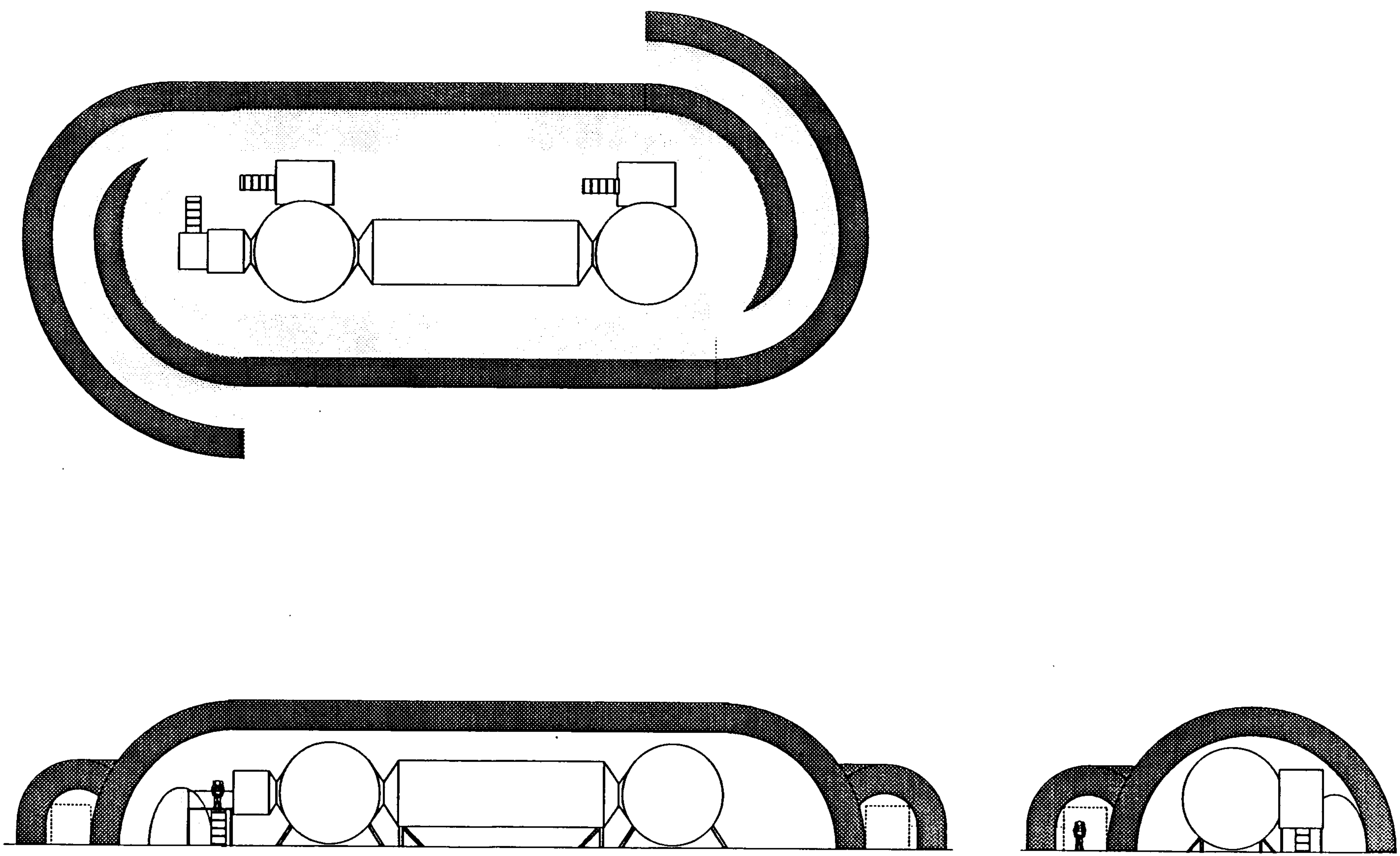

Figure 1

DRM Lunar Base, Cutaway Views

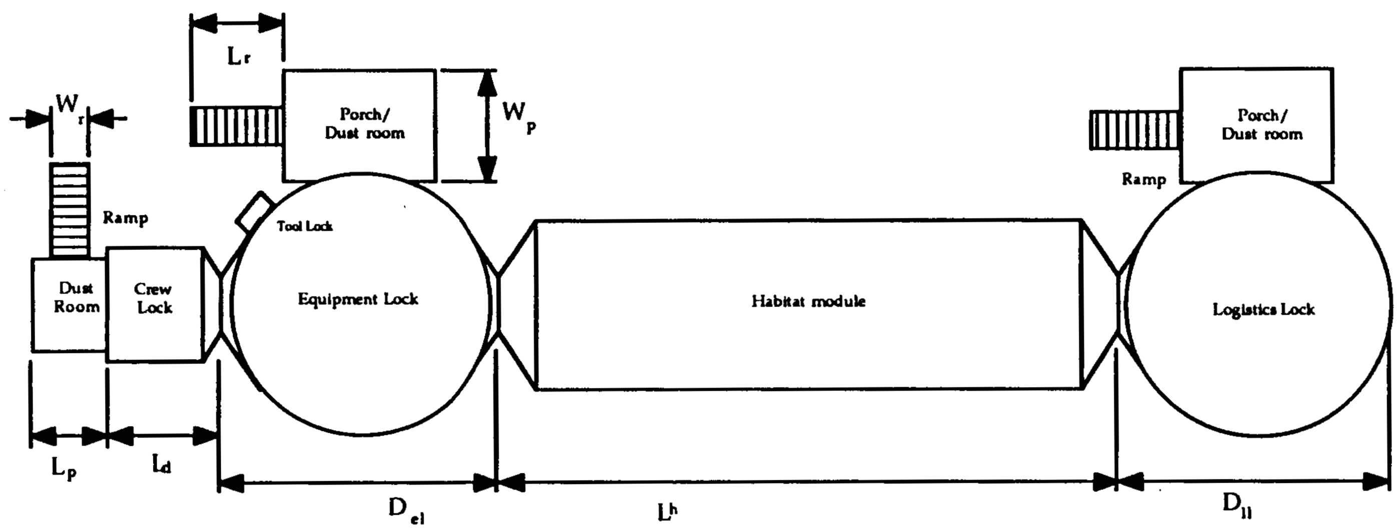

Figure 2
DRM Layout of Lunar Habitat

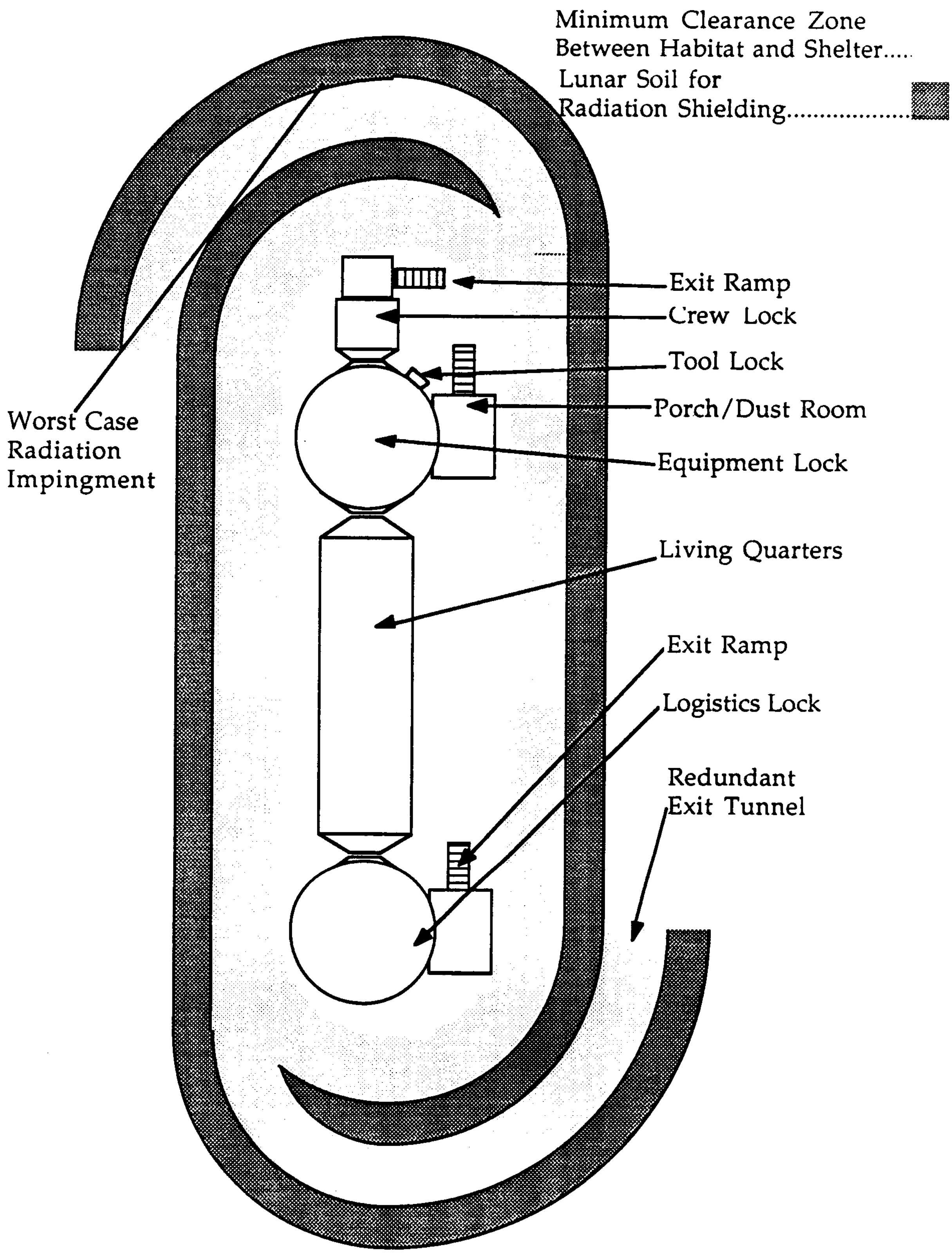

Figure 3
DRM Lunar base with radiation enclosure